Working Atmospheres

Atmosphere-Supply Systems in Post-War UK

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Contents

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Abstract

Using industry archives, this thesis examines the use of atmospheric information within the post-war UK electricity, gas, and water industries for the purpose demand and supply management. In doing so, I uncover a form of atmospheric study that existed outside the bounds of meteorological institutions—*atmosphere-supply studies*—that drew upon the atmosphere as a valuable resource in order to allow these crucial supply systems to function effectively. Across the industries in question, I identify three distinctive strands to this form of study. Firstly, the atmosphere became a *diagnostic tool*, where atmospheric information was used to identify and isolate trends is supply and demand that would potentially lead to system inefficiencies or failures. Secondly, the atmosphere became an *optimisation tool*, where atmospheric information was used to synchronise supply and demand, leading to the reduction of redundancies and their associated costs. Finally, the atmosphere became a *planning tool*, where atmospheric information was used to normalise long-term demand forecasts that informed the development of these supply systems. I show how workers within these industries metamorphized atmospheric information that they received from the Meteorological Office or collected themselves, reconstructing the weather as an entity that corresponded with changes in consumption in a simple, often linear, fashion. I also show how industry planners constructed climate as a static probability distribution in order to determine acceptable levels of failure. In doing so, I contribute to a larger shift in literature that deconstructs the divide between the atmosphere and societies, and question the view held by some within the World Meteorological Organization and the meteorological applications industry that greater quantities of higher quality atmospheric information will emancipate the greater part of the population from the effects of climate change.

Declaration

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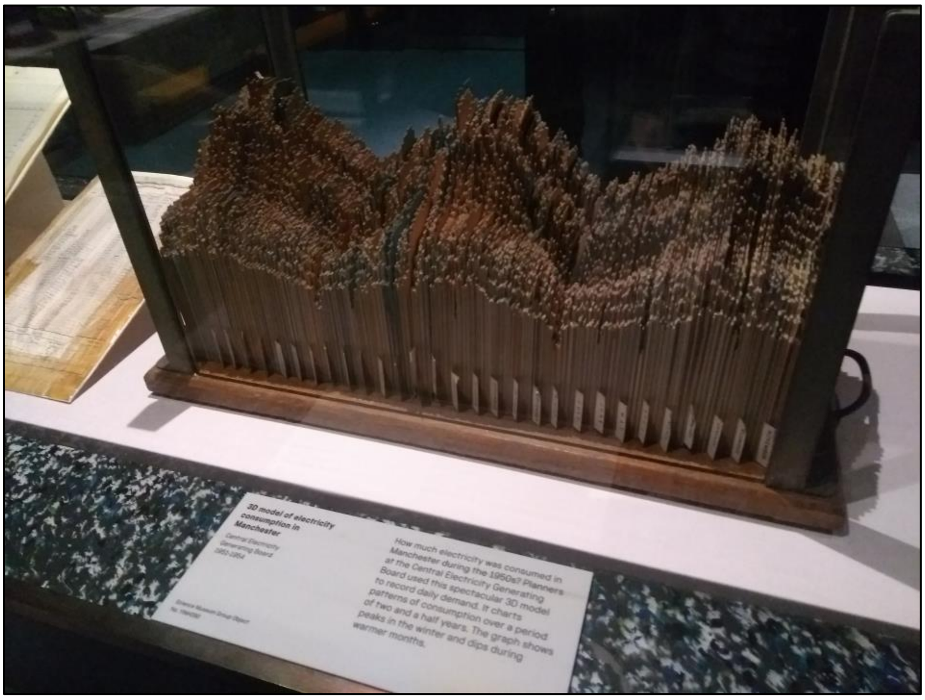
Chapter One—Introduction

In 2018, I had the pleasure of visiting Manchester's Museum of Science and Industry. It was an intensely "atmospheric" experience. The ostensive star of the show was Stephenson's Rocket, on loan from London's Science Museum, one of the machines that pioneered the conversion of atmospheric oxygen into forward motion. The aircraft that filled the Air and Space Hall itched to be in the sky, but the leaking roof brought the Manchester atmosphere down to them instead. That same damp Manchester atmosphere, so it is claimed, was ideal for the processing of cotton that fuelled the city's rapid industrialisation, the subject of one of the museum's permanent exhibits. However, the object that most grabbed my attention was not as familiar to me as spinning mules, Spitfires, or Stephenson's Rocket. From a distance, it resembled a model of a soaring mountainous landscape, with three evenly interspaced peaks trapped within an enclosing frame. As I drew closer, the object became more mysterious. It was made out of thin cardboard slices that came together to form the regular peaks, but these slices *did not behave*. There was a randomness that offended the overarching order—the surfaces of the peaks danced like a lake in the breeze, and on occasion the mountains were sliced through as if by a giant's knife (Figs. 1, 2).

The caption read:

> **3D model of electricity consumption in Manchester**
>
> Central Electricity Generating Board 1952–1954
>
> How much electricity was consumed in Manchester during the 1950s? Planners at the Central Electricity Generating Board used this spectacular 3D model to record daily demand. It charts patterns of consumption over a period of two and a half years. The graph shows peaks in the winter and dips during the warmer months.



3D model of electricity consumption in Manchester

Central Electricity Generating Board

How much electricity was consumed in Manchester during the 1950s? Planners at the Central Electricity Generating Board used this spectacular 3D model to record daily demand. It charts patterns of consumption over a period of two and a half years. The graph shows peaks in the winter and dips during warmer months.

Figure 1. Electricity demand model as photographed by the author on October 19, 2018. The caption can be seen in front.

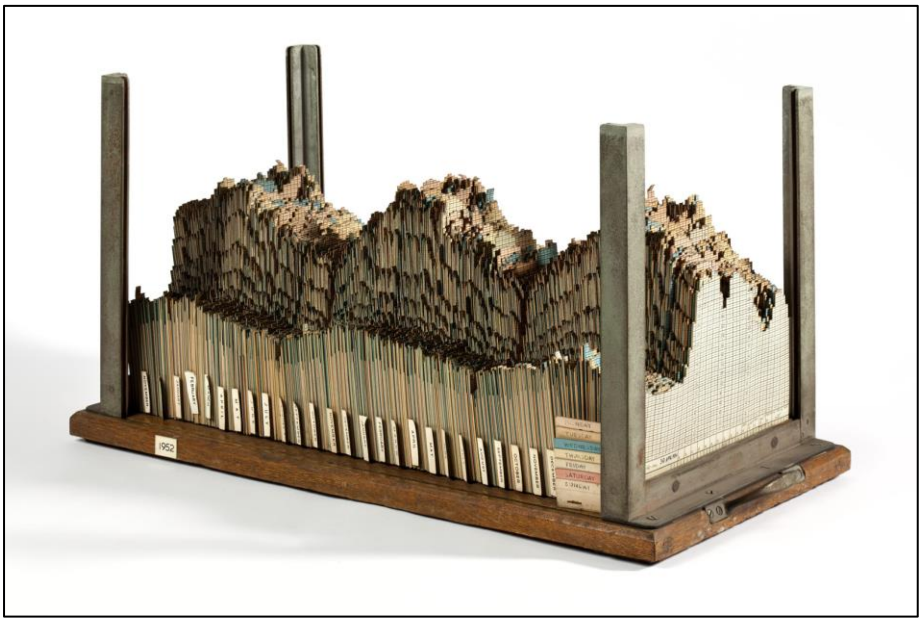


Figure 2. Electricity demand model as photographed by Alice Cliff and Jenny Rinkinen. The yearly demand curve traverses the long axis, and the daily demand curve traverses the short axis.[1]

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[1] Alice Cliff and Jenny Rinkinen, “Visualising Electricity Demand: Use and Users of a 3D Chart from the 1950s,” *Science Museum Group Journal* 9, no. 09 (2018).

For me, this immediately transformed the object from something interesting into something fascinating. Here was a record of how a city of 2.7m lived more than half a century ago. I could see the initial sharp incline as people woke up to go to work and factory managers switched on machines, a dip where these machines were switched off as workers went on their lunch break, and a rise where tired employees arrived home and switched on their lights, televisions, and electric heaters. The regimen of industrial life was represented by the uniformity of the daily cycle. But even more fascinating, I thought, was the fact that the literal and metaphorical power of industry could not resist being sculpted by Manchester's atmosphere, leading not only to large seasonal variations but daily fluctuations that registered as a noisy surface on the model. Electric lights and heating shielded much of lived experiences from the erratic atmosphere, but for power engineers the erratic atmosphere was central to the functioning of their systems, even to the extent that they would create this beautiful object out of hand cut pieces of cardboard with the *Manchester Guardian*'s daily weather summaries recorded on each slice.[2]

This was a handmade object that demonstrated a handmade process—millions of switches being flicked on a daily basis as a result of often subconscious decisions made in the context of atmospheric conditions. The people of 1950s Manchester, much the same as people today, switched on the heating when it was cold and windy, flicked light switches when it was overcast, and warmed electric irons when clothes could not be dried outside. Each one of these decisions contributed to the overall system demand. This thesis is about how the relationship between the atmosphere and demand came to be understood and exploited by the UK utilities industries. This was done through a form of atmospheric study that existed within industry rather than in meteorological institutions, but nevertheless

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[2] Cliff and Rinkinen.

became one of the main vectors by which the atmosphere supported the lives of ordinary people during ordinary days.

Thesis Aims

This thesis traces the emergent use of formalised atmospheric information within the UK electricity, gas, and water systems with a post-war focus. The expansion of these industries was an essential prerequisite for post-war economic growth, and atmospheric information became essential for their operation and planning. I wish to understand how atmospheric information was processed within these industries for the purposes of forecasting demand, asking how this information, which was often produced for very different purposes within meteorological institutions, was made into an essential component of the large technological systems that these industries stewarded. In addition, I hope to explore the factors that motivated these industries to take an interest in atmospheric information, asking why atmospheric information came to be seen as a valuable resource that helped systems function effectively. I will explore the role of system *optimisation*—the reduction of the material and temporal gap between supply and demand—in making atmospheric information an increasingly exploitable resource, and how atmospheric information reciprocally contributed to optimisation and the reduction of redundancies within systems. I will also examine the role of planning, as well as the possible impact of landmark climate events in making the atmosphere more visible to system managers. I trace the development of and the motivations for a form of atmospheric study, intimately embedded and motivated within the functioning of large technological systems, that existed outside the walls of meteorological institutions.

By choosing these particular systems, I hope to gain an insight into how atmospheric information came to be used by organisations that straddle the public and private spheres. In the post-war period the utilities were mostly nationalised although but were not controlled directly by government, rather by government appointment. Nevertheless, ministers and parliamentary committees publicly gave their opinions on how the systems were run. I hope to draw out the contrast between how atmospheric information was conceptualised between different groups, whether members of industry, government, or regulators. I am especially interested in the viewpoint and practice of those who directly oversaw these systems, and how their conceptualisation of a useful atmosphere compared to viewpoints within the institutional bounds of applied meteorology and climatology.

The rest of this chapter reviews key sections of literature that this thesis speaks to. Firstly, I review the literature that explores and deconstructs the relationship between the atmosphere and society, amongst which this thesis resides. Established histories show how during the post-war period a large part of atmospheric study broke free from its applied origins, forming a new global-scale “atmospheric science.” This thesis highlights a less-explored form of atmospheric study that mostly emerged in the same period due to changes in the national economy. This form of study conceptualised the atmosphere as a local or national phenomenon, allowing this thesis to challenge the idea that the atmosphere at a national scale became less relevant during the twentieth century. Next, I review how the atmosphere has been promoted as a useful entity through the conceptualisation of the *atmospheric resource* between the 1940s and 80s, and how this conceptualisation was made to resonate with changing societal priorities. This thesis contributes to the revival of the atmospheric resource conceptualisation, bringing the atmosphere into wider debates about how useful objects and spaces should be managed. I then examine attempts to attach monetary valuations to atmospheric information, mostly by those within the bounds of institutional meteorology and climatology. This thesis shines new light on how atmospheric information became valued within large technological systems, which often went beyond the bounds of simple monetary valuation. I then consider the rise of commercial weather services, and ask whether the growth of the quantity and quality of atmospheric information has made systems more resilient against atmospheric changes. My thesis traces reciprocal changes between technological systems and atmospheric information, and shows how many of these changes make systems less resilient to unpredictable external changes such as climate change. Next, I review the literature on how atmospheric information has been transferred and processed, an area that my thesis can contribute to with its historical industry-based perspective. Finally, I examine the historical literature on operational research, a research area that many of the main actors in this thesis identified with.

Weather, Climate, Society

As stated previously, this thesis uncovers a form of atmospheric studies that largely exists outside of the bounds of meteorological institutions. In many ways, these "atmosphere-supply studies," as I call them, could be considered to be relatively basic—the mathematical tools rarely went beyond various forms of correlation. Nevertheless, atmosphere-supply studies took up a considerable investment of time within the post-war UK utilities. Staff within these industries produced thick reports on the subject, which were often condensed down to articles in peer-reviewed journals. However, despite sometimes having an awareness of key climatological debates in academia, almost none of these staff identified as meteorologists, climatologists, or atmospheric scientists. The journals that they published in were usually industry-specific, or in managerial subjects such as operational research. These engineers and managers were studying the atmosphere, but it is difficult to claim that they were undertaking applied meteorology or climatology. By uncovering a form of atmospheric study that was deeply embedded in the functioning of large technological systems, this thesis adds to a turn in the literature that deconstructs the divide between the atmosphere and society, echoing broader trends deconstructing the separation of the “natural” and human worlds.[3]

In May 2008, historians, sociologists, and anthropologists of environmental knowledge gathered in Rio de Janeiro for the conference “Weather, Local Knowledge and Everyday Life,” leading to a published volume. In the introduction to this volume, weather historians Vladimir Janković and Christina Barboza state that “meteorology is not always about the weather. Nor is the weather always the subject of meteorological science.”[4] This work expanded weather studies beyond the bounds of meteorological science, incorporating, for example, indigenous knowledges, discussions of political economy, and studies of culture. In his own contribution, Janković investigated how the outdoor garment industry allowed a select few to transcend the weather, contributing to a troubling wider trend that aims to eliminate environmental contingency through expensive consumer products. Janković claims that histories such as these had been hidden by a “megalomaniacal” privileging of climate and weather as “global” physics-based phenomena, which hinders attempts to downscale the weather into daily lived experiences.[5] By showing how daily lived experiences of weather shaped large technological systems, this thesis shows how managers and engineers both rescaled the weather into an overall demand curve on (up to) a national scale.

Marc Tadaki, Jennifer Salmond, and Richard Le Heron criticised the understanding of “climate” and “society” as stable entities with standard modes of association. They argued

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[3] Bruno Latour, *We Have Never Been Modern* (Cambridge, Mass: Harvard University Press, 1993); Val Plumwood, *Feminism and the Mastery of Nature* (Routledge, 1993); Yrjö Haila, “Beyond the Nature-Culture Dualism,” *Biology and Philosophy* 15, no. 2 (March 1, 2000): 155–75.

[4] Vladimir Janković and Christina H. Barboza, “The Many Lives of Weather,” in *Weather, Local Knowledge and Everyday Life*, ed. Vladimir Janković and Christina H. Barboza (Museu de Astronomia e Ciências Afins, 2009), 15.

[5] Vladimir Janković, “The End of Weather: Outdoor Garment Industry and the Quest for Absolute Comfort,” in *Weather, Local Knowledge and Everyday Life*, ed. Vladimir Janković and Christina H. Barboza (Museu de Astronomia e Ciências Afins, 2009), 172–80.

that applied climatologists have positioned their work within the “politics of the biophysical”, which emphasises “true” positivist relationships rather than social, economic, or political questions and reproduces funding priorities and problem framings. They identify several areas where the biophysical framing is inadequate, including climate-change adaption, the commercialisation of climate science, and climate services for development. Instead, they advocate for a “cultural climatology,” where social, economic and political questions come to the fore, and where human-atmospheric relations are *assembled*.[6] Although the focus for this thesis exists outside the bounds of “applied climatology,” it nevertheless examines many of the positivist relationships that make up the politics of the biophysical. However, this thesis also explores “behind the scenes” to examine the political goals that reciprocally gave rise to the construction and use of these positivist relationships, providing an important historical context to Tadaki et al.’s claims.

In a 2017 book, professor of climate and culture Mike Hulme reframed “climate” as emerging at the interface between human experience of the weather and cultural practice.[7] For Hulme, mathematically orientated definitions of climate such as those promoted by the World Meteorological Organization “do not do justice to the deep material and symbolic interactions which occur between weather and cultures and places.”[8] For Hulme, the idea of climate provides a normative framing through which people can come to grips with the chaos and unpredictability of weather. The idea of climate creates cultural expectations of the weather, without which discussions that start with “strange weather we’re having today” would be impossible. Later in the book, Hulme joins with Janković and others in critiquing “global” framings of climate, describing how the

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[6] Marc Tadaki, Jennifer Salmond, and Richard Le Heron, “Applied Climatology: Doing the Relational Work of Climate,” *Progress in Physical Geography: Earth and Environment* 38, no. 4 (August 1, 2014): 392–413.
[7] Mike Hulme, *Weathered: Cultures of Climate*, First edition (London: SAGE Publications Ltd, 2016).
[8] Hulme, 2.

human experience of climate never remains static as people move and cultures change. This thesis provides a detailed account of how climate was “constructed” within the UK electricity, gas, and water industries, showing how mathematical treatments were used to force historical climate datasets into a stable configuration, therefore allowing these industries to come to grips with the weather in a similar way to the cultural process described by Hulme.

This thesis explores the transfer of atmospheric information in the context of large technological systems. Although histories of atmospheric science explore atmospheric information extensively, in a post-war context they rarely explore the transfer of information between the “scientific” realm and outside activities in any depth. Indeed, much of the historiography of the atmosphere focuses on how a large section of atmospheric study broke free (or was appropriated) from its applied origins, becoming an institutionalised area of study in its own regard: “atmospheric science.”[9] Spencer Weart, a historian of physics, claims that during the first half of the twentieth century, meteorology and climatology were considered professions rather than established fields of physical science. Climatology consisted of the process of collecting region-based statistics for the benefit of interested industries such as agriculture, and meteorology largely consisted of the creation trial and error forecasts for shipping and aviation. Where the university researchers studied climatology, they did it within geography departments with a limited mathematical basis. Weart argues that concerns surrounding climate change in the 60s and 70s prompted diverse subjects to coalesce, forming explicitly interdisciplinary journals as

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[9] James Rodger Fleming, *Inventing Atmospheric Science: Bjerknes, Rossby, Wexler, and the Foundations of Modern Meteorology* (MIT Press, 2016); Robert Marc Friedman, *Appropriating the Weather: Vilhelm Bjerknes and the Construction of a Modern Meteorology* (Ithaca: Cornell University Press, 1989); Matthias Heymann and Dania Achermann, “From Climatology to Climate Science in the Twentieth Century,” in *The Palgrave Handbook of Climate History*, ed. Sam White, Christian Pfister, and Franz Mauelshagen (London: Palgrave Macmillan UK, 2018), 605–32.

well as exploiting existing ones such as *Science* and *Nature* in order to communicate.[10] Weart's narrative suggests a progression in the post-war period from atmospheric studies originating within industry towards atmospheric studies forming the basis for a new academic area of study. My thesis complicates this view, showing how new forms of atmospheric study also emerged within industry during the same period.

There are a small number of history-oriented works that explore the transfer of weather information outside of academic circles in a post-war context, amongst which the present work nestles. Janković provides an account of key developments in applied meteorology and climatology, arguing that four main factors drove the growth of the subject area. Firstly, he argues that an "atmospheric resource" agenda strengthened during the 1960s, which was caused by, amongst other factors, the rise of weather modification narratives, the development of computers required for numerical assessment of the weather resource, and mounting losses due to extreme weather events. Secondly, Janković argues that the assessment of the monetary value of weather was required in the context of budgeting for national weather services. Thirdly, he argues that mounting weather-related losses in the 60s and climate anomalies in the 70s caused "political tensions, environmental soulsearching, and security crises" in relation to the atmosphere. Finally, he argues that the rise of the climate impact assessment in the late 70s pushed the need to assess the monetary impacts of weather. However, Janković does not delve deeply into literature within key industries, instead mainly relying on sources provided by academia and policymaking, which in my opinion too often treat diverse industries monolithically, and as largely passive, in the context of weather information. In addition, Janković focuses on weather losses rather than the use of weather information to improve operational

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[10] Spencer Weart, "Rise of Interdisciplinary Research on Climate," *Proceedings of the National Academy of Sciences of the United States of America* 110 (2013): 3657–64.

procedure.[11] This thesis aims to provide new perspectives on the atmosphere as a useful entity based upon literature and archival material found within the industries it examines.

The US and the UK took very different approaches to weather information following the Second World War. In the UK, the Meteorological Office largely maintained a monopoly over the collection, interpretation, and dissemination of weather data. In the US, Weather Bureau data was made freely available, albeit with little interpretation or processing. Consulting meteorologist David Spiegler identifies the end of the Second World War as an important accelerant for private sector meteorology in the United States, as wartime meteorologists who had developed specific operational forecasts for the military found themselves unemployed. As a result, several founded their own forecasting companies. The forecasts they provided had a higher spatial and temporal resolution than those provided by the National Weather Bureau and were more tailored to the specific needs of clients. In addition, many utility companies and airlines hired their own in-house meteorologists. Spiegler highlights the 1960 foundation of the Travelers Research Centre, a subsidiary of the Travelers Corporation insurance company, as an important moment. The Travelers Research Centre worked on understanding the occurrence and trajectories of hurricanes, and Spiegler argues that losses occurring from a series of hurricanes in the mid-1950s prompted the subsidiary’s foundation. Another important facilitator for the development of private sector meteorology was the 1970 Clean Air Act, which mandated federal and state governments to monitor air quality and prepare impact statements.[12]

The commercialisation of atmospheric information did not just occur within the private sector. In a UK context, historian of science Alex Hall has explored the commercialisation of

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[11] Vladimir Janković, “Working with Weather: Atmospheric Resources, Climate Variability and the Rise of Industrial Meteorology, 1950–2010,” *History of Meteorology* 7 (2015): 98–111.

[12] David B. Spiegler, “A History of Private Sector Meteorology,” in *Historical Essays on Meteorology 1919–1995: The Diamond Anniversary History Volume of the American Meteorological Society*, ed. James Rodger Fleming (Boston, MA: American Meteorological Society, 1996), 417–41.

Meteorological Office services. Immediately after the war in the era of reconstruction, the Meteorological Office made little distinction between enquiries made by public or private organisations, with only small, subsidised charges being levied on repeated private enquiries. Oliver Graham Sutton, a new director appointed in 1953, pursued a strategy which relied more on the provision new services to justify the Meteorological Office's budget. However, his expansionist ambitions were reined in by a committee appointed by the sponsoring Air Ministry, which demanded that the Meteorological Office follow a more cost-effective model. As a result, the Meteorological Office began actively seeking out clients for its existing services and founded regional centres to facilitate tailored information for local clients. This new commercial orientation was reflected by a change in language, as "users" became "customers."[13] This thesis aims to give the client perspective of Hall's narrative—what wider political and economic changes gave rise to new demands for atmospheric information? How did new clients emerge?

American Studies scholar Bernard Mergen dedicated a portion of a wide-ranging 2008 volume to the development of a "discomfort index" by the US Weather Bureau in 1959, which attempted to measure the human body's response to various temperature and humidity.[14] According to Mergen, in the late 1950s "the U.S. Weather Bureau was suffering from one of its periodic crises of identity and struggling to improve its public image." As a result, the Bureau offered a new service that would connect better with everyday lives. Earl Thom of the Bureau developed the index by combining the dry-bulb temperature and the wet-bulb temperature with a simple equation. A discomfort index of 80 or above was said to make almost everyone miserable. The US media reaction was mostly negative, with some commentators suggesting that the index would lead to tardiness and weather-based

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[13] Alexander Hall, "From the Airfield to the High Street: The Met Office's Role in the Emergence of Commercial Weather Services," *Weather, Climate, and Society* 7, no. 3 (July 2015): 211–23.

[14] Bernard Mergen, *Weather Matters: An American Cultural History Since 1900* (University Press of Kansas, 2008), 306–7.

hypochondria. The discomfort index is an example of a synthetic weather variable designed to reflect how the atmosphere was felt by human bodies, and I will be able to add a new dimension to this account by examining the earlier systematic creation of similar weather variables within industry (e.g. demand forecasting variables in the electricity industry).

In his PhD, historian of meteorology Roger Turner explored the rise of aeronautical meteorology, showing how the area of study emerged through the experience of pilots in the first half of the twentieth century. In this case, Turner identifies meteorology as an "infrastructural science", which is organizationally intensive and invisible applied science. Infrastructural science supports the management of large technological systems that, despite underpinning modern ways of living, are invisible unless they fail. Turner emphasises the co-ordinated collection of large datasets through routine observations by a large number of individuals with moderate technical training, and presents aeronautical meteorology as a collaborative process between meteorologists and pilots, an integration of theory-derived knowledge and observation.[15] The atmosphere-supply studies explored in this thesis share many of the same characteristics of infrastructural science, although atmosphere-supply studies resist the label of "applied science." Often, individuals within the utilities industries were working against how weather and climate information was processed within scientific institutions such as the Meteorological Office.

Geographer and historian of meteorology Samuel Randalls has explored the information transfer involved in "weather derivatives"—financial instruments used in the utilities industries that can be analogised as weather insurance that is activated through pre-requisite weather conditions rather than resultant financial loss. Randalls shows how catering to these demands created tensions between financial traders and meteorologists,

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[15] Roger Turner, "Weathering Heights: The Emergence of Aeronautical Meteorology as an Infrastructural Science," *Publicly Accessible Penn Dissertations*, May 17, 2010, accessed September 14, 2022, https://repository.upenn.edu/edissertations/147.

helping shape the data for new priorities and purposes.[16] In another work, James Kneale and Randalls consider the "hidden" meteorological knowledge in the nineteenth century insurance industry, aiming to "capture expertise beyond the formally recognized meteorological science."[17] My project will aim to uncover the expertise beyond formally recognized meteorological science in the post-war period, and how atmospheric information was shaped for the purpose of forecasting demand.

This thesis adds a rich new strand to this discourse blurring the line between the atmospheric and the societal, adding further critique to the politics of the biophysical with regard to atmospheric knowledge. As will be shown, the use of atmospheric information within industry was rarely apolitical. My thesis also contributes to critiques of a "global" atmosphere by outlining new local and national atmospheres that arose during the twentieth century. The way that atmospheric information was processed in these industries was usually highly dependent upon the specific cultural response to atmospheric conditions (e.g. the use of air conditioning) as well as the rhythms of economic life, making the atmospheric information culturally and economically contingent through its processing. By unveiling a form of atmospheric study that is deeply embedded in the operation and developmental path of large technological systems, this thesis adds another dimension to the scholarship that deconstructs the divide between the atmosphere and society.

Resurrecting National Weather

One of the key discussion-points in atmospheric history literature has been one regarding atmospheric scale. Broadly speaking, the traditional telling of the social history of the atmosphere has been that of the transfer of agency from folk knowledge to national

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[16] Samuel Randalls, "Weather Profits: Weather Derivatives and the Commercialization of Meteorology," *Social Studies of Science* 40, no. 5 (October 2010): 705–30.

[17] James Kneale and Samuel Randalls, "Invisible Atmospheric Knowledges in British Insurance Companies, 1830–1914," *History of Meteorology* 6 (2014): 35–52.

weather services, then national weather services to global networks.[18] The local or individual atmosphere becomes national, and the national atmosphere becomes global. This has been reflected by changes in discourses in wider publics, with discussion of *global* warming taking precedence over individual experiences and events. However, as hinted at above, there has recently been a backlash against the conceptualisation of the atmosphere as a global phenomenon, with some scholars arguing that the atmosphere only becomes relevant to everyday lives when it is conceptualised at everyday scales.[19]

Nevertheless, there appears to be a consensus in the literature that whether the atmosphere is global, local, or individual, it is no longer national. This thesis argues that the atmosphere at a national scale not only continues to exist, but in many ways became more relevant during the twentieth century, not less as much of the literature would suggest. I recount the twentieth-century formation of a form of weather study that was intimately linked to the rhythms of industrial life, which were in turn dictated by national legislation regarding acceptable working practices. This had an effect on which atmospheric information became important or valuable, for example during the hour of peak daily electricity demand, which usually occurred straight after working hours. In addition, I emphasise the development of nationally integrated supply systems, most notably the electricity supply system, the managers of which had to understand weather-dependent changes in supply and demand on a national scale—the local or individual atmosphere was largely smoothed out in the case of electricity. In doing so, I challenge the dichotomy of the

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[18] Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, Massachusetts; London, England: MIT Press, 2010); Weart, “Rise of Interdisciplinary Research on Climate”; Joshua P. Howe, *Behind the Curve: Science and the Politics of Global Warming*, 1st ed. (Seattle; London: University of Washington Press, 2014).

[19] Janković, “The End of Weather: Outdoor Garment Industry and the Quest for Absolute Comfort”; Steve Rayner, “Weather and Climate in Everyday Life: Social Science Perspectives,” in *Weather, Local Knowledge and Everyday Life*, ed. Vladimir Janković and Christina H. Barboza (Museu de Astronomia e Ciências Afins, 2009), 19–36; Elizabeth Shove, “Manufacturing Weather: Climate Change, Indoors and Out,” in *Weather, Local Knowledge and Everyday Life*, ed. Vladimir Janković and Christina H. Barboza (Museu de Astronomia e Ciências Afins, 2009), 37–43.

global and individual scale of the atmosphere in the literature, showing how the national scale still has much to offer in terms of analysis.

The Atmospheric Resource

Through its focus on the integration of the atmosphere into the national economy, this thesis joins others in constructing the atmosphere as a valuable *resource*—as an object that can be drawn upon to help organisations and systems operate efficiently. In doing do, it helps draw the atmosphere into wider long-lasting debates regarding how useful objects and spaces should be managed, whether through private ownership, common ownership, greater regulation, or something else entirely.[20] Although these debates have recently returned to prominence with regard to potable water,[21] outer space,[22] and ocean floors,[23] they have become elusive with regard to the atmosphere, one of the most ever-present objects in human life on earth. However, until the 1980s brought in the IPCC climate change framing of science, impacts, and response to the fore, the atmosphere was often conceptualised as a resource, mainly for the purpose of highlighting its importance as an essential component of the national economy and everyday life.

Although weather and climate had long been included before in geographical overviews of natural resources, the explicit definition of the atmosphere itself as a resource appears to have emerged in the United States just before its entry into the Second World War, at a time when US scientists more generally were becoming more receptive to being enlisted in

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[20] E.g. Garrett Hardin, “The Tragedy of the Commons,” *Science* 162, no. 3859 (December 13, 1968): 1243–48; Robert J. Smith, “Resolving The Tragedy of the Commons By Creating Private Property Rights In Wildlife,” *The Cato Journal* 1, no. 2 (1981): 439–68; Susan Jane Buck Cox, “No Tragedy of the Commons,” *Environmental Ethics* 7, no. 1 (1985): 49–61.

[21] Erik Swyngedouw, “Dispossessing H2O: The Contested Terrain of Water Privatization,” *Capitalism Nature Socialism* 16, no. 1 (2005): 81–98.

[22] Rossana Deplano, “The Artemis Accords: Evolution or Revolution in International Space Law?,” *International & Comparative Law Quarterly* 70, no. 3 (July 2021): 799–819.

[23] Erik E. Cordes and Lisa A. Levin, “Exploration before Exploitation,” *Science* 359, no. 6377 (February 16, 2018): 719.

government-led economic amelioration as a result of the economic challenges of the 1930s.[24] In 1941, Francis Reichelderfer, the Director of the United States Weather Bureau, boldly stated that “Weather and Climate are as vital to human life as the soil itself. They are among our most valuable natural resources.”[25] He outlined the various uses of weather and climate information, including by power companies, agriculture, and the military. These words opened Reichelderfer’s contribution to the US Department of Agriculture publication *Climate and Man*, the sixth volume in a series designed cover the “major aspects of science” that, as put in the foreword by Secretary of Agriculture Claude R. Wickard, were “fundamental to the use of our agricultural resources.”[26]

The concept of an atmospheric resource was soon taken up by Helmut Landsberg, one of the most prominent climatologists of the twentieth century (Fig. 3). Arriving in the US in 1934, Landsberg had a background in geophysics, and began his American career researching for the Pennsylvania mining sector at a time when this industry was an epicentre of government-led relief. Historian of science Gabriel Henderson argues that in this role Landsberg quickly subscribed to the idea that science in service of the state and citizens was no vice.[27] In 1941, Landsberg published his first monograph on climatology, *Physical Climatology*, which emphasised his developing view that climatological information derived its value from being useful to wider society: “The present age, with an increasing world population, is interested in a stabilization of its economic state; fluctuations brought about by outside factors are undesired […]”[28] Landsberg was

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[24] “Karl Compton, Isaiah Bowman, and the Politics of Science in the Great Depression,” *Isis* 76, no. 3 (September 1985): 301–18.
[25] Francis W. Reichelderfer, “The How and Why of Weather Knowledge,” in *Climate and Man*, ed. Gove Hambridge (Washington D.C.: U.S. Government Printing Office, 1941), 129.
[26] United States Dept of Agriculture, *Climate and Man* (U.S. Government Printing Office, 1941), vii.
[27] Gabriel D. Henderson, “Helmut Landsberg and the Evolution of 20th Century American Climatology: Envisioning a Climatological Renaissance,” *WIREs Climate Change* 8, no. 2 (2017): e442.
[28] Henderson, 5.

interested in using climatology to bring about a future that was brighter—a way out of the economic instability of the 1930s.

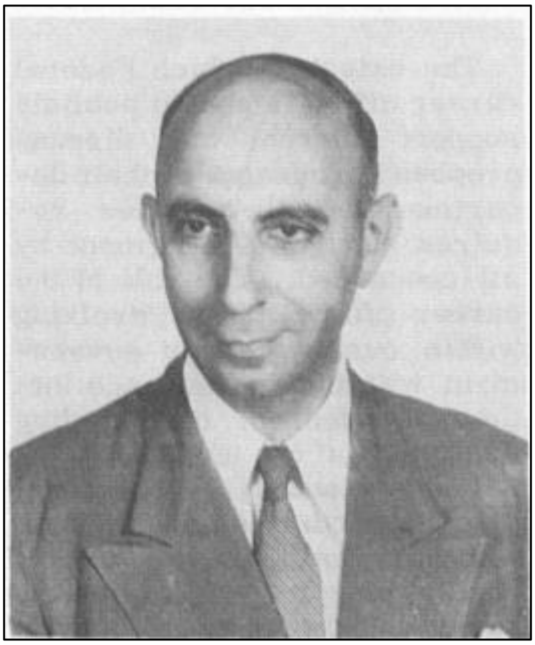

Figure 3. Helmut Landsberg circa 1962[29]

It is against this backdrop, and during a short stint working for the US Weather Bureau, that Lansberg published the 1946 paper *Climate as a Natural Resource*, which explicitly laid out his rationale behind defining climate as such. Landsberg opens by declaring that "The climate is part of the natural endowment of a country. In some regions it imposes hardships on the inhabitants, in others it makes life easy."[30] Landsberg's paper forms a call to action for long-term climate information to be more extensively collected and efficiently collated. Landsberg's conceptualisation of a climatic resource was very much focused around the idea of a "national economy" and "long-range planning"—he does not talk about companies and shareholders as beneficiaries and in fact makes no numerical financial estimates at all. Landsberg's climatic future was a future for all. He bemoans the

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[29] United States Weather Bureau, *Image of Helmut Landsberg, circa February 1962*, Circa 1962, Photograph, Circa 1962, NOAA.
[30] Helmut Landsberg, "Climate as a Natural Resource," *The Scientific Monthly* 63, no. 4 (1946): 293.

exclusive use of climate information for military purposes: “Is climate an important piece of intelligence only in the grim business of killing people in the most efficient manner? The answer is an emphatic *No!*”[31] He makes repeated reference to the idea that climate is an “inexhaustible” resource, making an analogy with the development of nuclear energy. He also values recreation “as an important balancing element in our lives” rather than simply an economic sector. For Landsberg, climatic resources were a way of creating a better world out of the ruins of the Second World War and the Great Depression: “Let us say in conclusion that the unlimited climatic resources of the United States still await exploration and exploitation; they wait to be tapped. They promise full returns by better adjustment of our homes and health, our agriculture and technology, to the atmospheric environment.”[32]

In 1951, ten years after he first identified weather and climate as resources of first-rate importance, Francis Reichelderfer took the inaugural presidency of the World Meteorological Organization. In this position, Reichelderfer used his opening entry in the World Meteorological Organization’s Bulletin to talk about “weather resources.” As in 1941, Reichelderfer’s interpretation of the atmospheric resource was much more engaged with predominant US economic paradigms when compared to Landsberg’s: “Many different kinds of businesses have found it worthwhile to apply weather information to their working plans and operations, for example: architecture, building supplies and construction, bus lines, chemical companies, coal and other fuel suppliers, confectionary manufacturers, dairies, farming of all kinds, fisheries, florists, food processors, hospitals, live stock ranches, lumber companies, public utilities including gas, light and power producers, railroads, restaurants, textile plants, and many others.” At the same time, Reichelderfer also appealed to “universality,” reflecting the language of UN institutions.

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[31] Landsberg, 294.
[32] Landsberg, 298.

Just like in 1941, Reichelderfer was using the weather resource conceptualisation to shore up support for his institution—this time the fledgling World Meteorological Organisation.[33]

In the UK, the conceptualisation of "climatic resources" was taken up by Arthur Austin Miller, an influential geographer who became the President of the Institute of British Geographers 1946-8. He had made his name through his 1931 textbook *Climatology*, which was later praised for moving past the "gazetteer" method of climatology that was still in vogue at the time.[34] His 1931 book also contained a substantial introduction that outlined the uses of climate, drawing on colonial discourses and motivations. Miller claimed that peoples could only successfully colonise climates that they were accustomed to, for example claiming that "North Europeans succeed best in Canada, South Europeans in Brazil." In fact, Miller emphasised that "This aspect of colonization is to-day one of the most important applications of climatic study."[35] After the war, as decolonization began to get under way, Miller changed his tune somewhat. In a 1956 presidential speech to the geography section of the British Association for the Advancement of Science, Miller conceptualised the climate of a country as one of its natural resources in a manner very similar to Landsberg. However, Miller also emphasised how recent societal changes had made "advanced" societies more sensitive to climate, for example highlighting how settlements were now positioned because of suitability for industry rather than access to water.[36] In a 1958 book co-authored with Martin Parry, Miller made the case for studying

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[33] Francis W. Reichelderfer, "Weather Resources," *World Meteorological Organization Bulletin* 2, no. 1 (January 1953): 2–5.

[34] David L. Linton, "Obituary: Emeritus Professor A. Austin Miller," *The Geographical Journal* 134, no. 3 (1968): 467–69.

[35] Arthur Austin Miller, *Climatology*, 1st ed. (Methuen & Company, Limited, 1931), 3.

[36] "Summaries of Addresses of Presidents of Sections: The Use and Misuse of Climatic Resources," *Nature* 178, no. 4531 (September 1956): 474. It should be noted that this source is only a summary of what was said.

the weather: “Knowledge of weather increases our power a million-fold for it places a giant’s strength behind our arm if we are wise enough to work in co-operation [with it].”[37]

Landsberg, Reichelderfer, and Miller had a lot in common. They all had their academic beginnings in areas outside of climatology or meteorology, specifically linked to extractive industries,[38] meaning that the conceptualisation of the atmosphere as a resource came more naturally for them. They were all also in positions of leadership, shoring up support for their subjects and institutions within ever-changing wider economies and societal norms. In the case of Reichelderfer and Miller, this meant fine-tuning the discussion to suit wider interests, very much acting in the vein of the politics of the biophysical that emphasise “true” positivist relationships rather than social, economic, or political questions. For Landsberg, however, the atmospheric resource was a tool for making a better world, inseparable from his vision for a better society.

Returning to Landsberg, one of the aims of his 1946 paper was to put climate, which he described as the unending procession of weather events, on the same level as weather when it came to institutional investment and attention. This distinction demonstrated an essential element of Landsberg’s climatic resource—that it was essentially static: “[…] the climate remains fairly constant, at least within a human lifetime. This fact makes it possible to treat climate as a calculable risk. Wherever climatic conditions are adequately known and described, they can be intelligently integrated into plans for all kinds of human activity.”[39] However, soon developments both within and outside meteorological discourse would question this assumption about an atmospheric resource, with the interlinked

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[37] Arthur Austin Miller and Martin Parry, *Everyday Meteorology* (London: Hutchinson, 1958), 253. This was partly said as a rebuke against advocates of weather modification.

[38] Miller began his undergraduate degree in chemical engineering, before switching to geology. Reichelderfer gained his undergraduate degree in chemistry and chemical engineering: “Arthur Austin Miller,” *Transactions of the Institute of British Geographers*, no. 46 (1969): xix–xxi; Jerome Namias, “Francis W. Reichelderfer,” Biographical Memoir (National Academy of Sciences, 1991).

[39] Landsberg, “Climate as a Natural Resource,” 293.

advent of weather modification and the push against “arid zones” forming standout issues. The atmosphere, so the arguments went, could the altered and the deserts could be pushed back to create new Edens.[40] By the late 1960s, the atmosphere began to be reframed under the concept of scarcity, reflecting wider discourse in the “crisis decade” of the 1970s.[41]

In 1968, the economist and geographer William Sewell, writing in the Bulletin of the American Meteorological Society, produced one of the more detailed analyses of the concept of an atmospheric resource, one focused on weather modification. Sewell was an influential scholar on resource management, advising the US and Canadian governments in this area, and was also active in promoting the management of atmospheric quality.[42] Sewell identified a social pecking order between resources, in which some could become “elite” in the sense that they “monopolize debate about resources in the Congress and they carve out the major share of funds allocated for resource development.” He then outlined five criteria required for the atmosphere to attain this status. Firstly, there had to be a perception that the resource was scarce, meaning that people would be willing to pay a price for its use. Sewell makes the case that a key component of the atmospheric resource—clean air in cities—had been made scarce and that the then-contemporary “revolt against pollution” showed that people were willing to pay for it. Secondly, the resource had to cause conflict between interested parties—the more the better—in order for the resource to accumulate a substantial body of political advocacy. He claimed that the

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[40] Matthias Heymann, “Climate as Resource and Challenge: International Cooperation in the UNESCO Arid Zone Programme,” *European Review of History: Revue Européenne d’histoire* 27, no. 3 (May 3, 2020): 294–320. For more on weather modification: James Rodger Fleming, *Fixing the Sky: The Checkered History of Weather and Climate Control* (Columbia University Press, 2010); Kristine C. Harper, *Make It Rain: State Control of the Atmosphere in Twentieth-Century America*, 1 edition (Chicago ; London: University of Chicago Press, 2017).

[41] Eric Hobsbawm, *Age of Extremes The Short Twentieth Century, 1914–1991*, New Ed edition (London: Abacus, 1995).

[42] Harold D Foster, “Obituary for William Robert Derrick Sewell 1931–1987,” *Natural Resources Journal* 29, no. 1 (1989): 3.

atmosphere was already a major source of conflict, as any change to the weather was going to help some people at the detriment of others. Thirdly, the resource had to be, in his word, “mothered”, preferably by well-resourced government agencies. Sewell identifies a swathe of agencies which could fill this role, but warns that if this responsibility is not well defined, the atmospheric resource could face either inaction or squabbling. Finally, the resource had to be able to elicit public investments and technological application, in order to attain development and status symbols (for example, enormous dams in the case of water management). Sewell argued that the opportunities for public funding existed in the research sector, and that weather modification offered the main platform of technological application. The main ingredient missing, so says Sewell, was a crisis to draw the elements together.[43] This discussion of scarcity, crisis and revolt is a far cry from Landsberg’s original hopes. The times had indeed changed.

In a similar vein, but working more from the original work of Landsberg, meteorological service administrator John Maunder, writing in 1970, claimed that growing awareness and concern over air pollution “is evidence of man’s growing appreciation of a limited climatic income.”[44] A more direct attack against any positive conceptualisation of a climatic resource was provided by geographer Allen Perry in 1971, who made explicit the links with prevailing discourse. Perry believed that the idea was contemporary, and linked it to wider realisations that resources were finite and sometimes severely limited: “until we know more about stratosphere troposphere interaction it might even be dangerous to call the atmosphere a renewable resource.”[45] The conceptualisation of an atmospheric resource was now being used as a tool to advocate conservation narratives. Geographer James

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[43] W. R. Derrick Sewell, “Emerging Problems in the Management of Atmospheric Resources: The Role of Social Science Research,” *Bulletin of the American Meteorological Society* 49, no. 4 (April 1, 1968): 326–36.

[44] W. J. Maunder, *The Value of the Weather* (Methuen, 1970), 1.

[45] A. H. Perry, “Econoclimate: A New Direction for Climatology,” *Area* 3, no. 3 (1971): 178–79.

Taylor outlined his conceptualisation of the atmosphere as a "social resource" in 1974. Taylor emphasised how the atmosphere was for the first time being evaluated from below, within and above: "Its evaluation as a resource of all kinds, not least social and also, inevitably, political, is achieving new dimensions and new meanings."[46] This expansion of what the atmospheric resource means was continued by John Thornes and Samuel Randalls. In a 2007 paper, they described the atmosphere as possibly the most valuable resource on Earth. Within this atmospheric resource envelope, they included the molecules in the atmosphere that allowed combustion engines to work, solar radiation and wind power, atmospheric information, and the commercial opportunities presented by climate change discourse.[47]

However, it is rare to find references to the atmospheric resource after the 1980s. Seeing the atmosphere as a resource which can be exploited neither resonates with environmentalism, which would rather not "exploit" the atmosphere, nor climate change discourse, which is dominated by the IPCC framing of science, impacts, and responses. In addition, the rise of privatisation in the 1980s made the idea of a "resource" that can be exploited by a "society" less relevant, as the main agency of exploitation fragmented into companies within sectors rather than central planners. This lack of the "atmospheric resource" conceptualisation been criticised recently by John Thornes et al., who believe that valuing the atmosphere economically is an important pre-requisite for proper management.[48] This thesis unveils what could be called a phenomenological atmospheric resource; the challenge posed to engineers was translating meteorological variables into variables that corresponded to people switching on their lights, heating, and water. Only by

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[46] James A. Taylor, *Climatic Resources and Economic Activity: A Symposium* (Newton Abbot: David and Charles, 1974), 40.

[47] John E. Thornes and Samuel Randalls, "Commodifying the Atmosphere: 'Pennies from Heaven'?," *Geografiska Annaler. Series A, Physical Geography* 89, no. 4 (2007): 273–85.

[48] John E. Thornes et al., "Communicating the Value of Atmospheric Services," *Meteorological Applications* 17, no. 2 (2010): 243–50.

doing this could the atmospheric resource manifest fully for the electricity, gas, and water industries. In addition, in embedding the atmosphere into political and economic debates surrounding essential infrastructure, this thesis highlights questions of how the atmospheric resource can be best managed, and how different groups manage it.

Weather's Price Tag

Although the atmospheric resource conceptualisation allows commentators to ask deeper questions of which societal regimes are best suited for governing the atmosphere, managers within meteorological institutions have long recognised that simply valuing the weather in explicit monetary terms best resonates with current societal paradigms that govern public expenditure. As might be expected due to his institutional interest and rather conservative outlook, Reichelderfer was an early proponent of assigning impressive monetary values to the output of the US Weather Bureau. In April 1940, not long after Reichelderfer became the Bureau's chief in December 1938, a questionnaire was sent the Bureau's field stations asking what their weather information was used for and approximate dollar values for their services.[49] By May 1940, most of these questionnaires had been returned, being heralded by the Weather Bureau's newsletter: "They have shown an estimated total value of our service beyond all expectations. The data and suggestions […] will be extremely useful in planning future Weather Bureau service and justifying public support of the Bureau's activities."[50] The same article conveyed Reichelderfer's personal thanks for the efforts in acquiring the data. Despite the results of the survey never being published, he wasted no time in using them. In his annual report to the Secretary of Agriculture in June 1940, Reichelderfer declared that the survey showed that the "savings

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[49] Francis W. Reichelderfer, "The United States Weather Bureau and Industry," *Weatherwise* 6, no. 2 (April 1953): 31–32, 62.

[50] "Questionnaire on Estimate of Weather Bureau Service," *Weather Bureau Topics and Personnel*, May 1940, sec. Information, 327.

attributed by business and industry to weather reports, forecasts, and warnings issued by the Bureau are more than 3 billion dollars annually."[51] As stated above, he then repeated this claim in the following year in the 1941 yearbook of agriculture.[52] Clearly Reichelderfer saw the three-billion-dollar figure as useful for his institutional interests.

However, it appears that this impressive statistic rested on very shaky ground.[53] Reichelderfer made two more public references to the same Weather Bureau survey in 1953, this time being a lot more vague about its findings. In his opening article in the World Meteorological Organization bulletin in January 1953, Reichelderfer made reference to the survey bringing "an amazing total as the annual increment in national income resulting from increased production and greater efficiency in operations made possible directly through applied meteorology."[54] He then highlighted how this total was many times the budget of the national weather service, but made no reference to what the total actually was or even the identity of the country in question. Reichelderfer was more candid in an article he published in *Weatherwise* in April 1953, when his audience was less likely to be administrators who had a say in his organisation's budget[55]:

> Although the survey did not attempt to include all of American business and industry, the sampling was sufficiently broad and representative to give an indication of the order of magnitude of weather service values, but the results were never published in detail because the figures were so large they would undoubtedly have been controversial! The total for the United States ran into ten figures annually. The survey served the purpose, however, of reminding us

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[51] Francis W. Reichelderfer, "Report of the Chief of the Weather Bureau," Annual Report (Weather Bureau, 1940), 3.

[52] Reichelderfer, "The How and Why of Weather Knowledge," 129.

[53] A later entry in the Weather Bureau newsletter suggests that the Bureau was more interested in impressive sounding lists rather than precise data: "Value of Weather Bureau Service," *Weather Bureau Topics and Personnel*, April 1941, sec. Field Service Topics, 444.

[54] Reichelderfer, "Weather Resources," 2.

[55] Reichelderfer, "The United States Weather Bureau and Industry," 31.

> again how weather and climate affect our daily lives and our means of livelihood.

Clearly, Reichelderfer was not being completely honest here. He was not embarrassed by the figures being so large, as he had used those same figures twice in in official reports during the 1940s. It follows that he was insecure about the methodologies being employed to come up with the three-billion-dollar figure, but had nevertheless used it anyway to shore up support for the US Weather Bureau's budget. Monetary value was an important framing for weather information going back to the beginning of the 1940s, even if the methodologies were undeveloped.

The incorporation of the weather into wider economic literature and discussion required changes from both economics and meteorology. Firstly, in order to incorporate numerical weather data, economics had to become a more intimately mathematical subject. This shift was finalised by the "Formalist Revolution" that took place in the 1950s, pushing for a highly mathematised approach across the whole of economics.[56] Secondly, forecasts had to become more statistically oriented rather than based on the forecaster's intuition. A 1950 paper by J. C. Thompson was instrumental in the development of statistical forecasts, becoming a touchstone for economic studies of weather information.[57] Thirdly, businesses had to become interested in optimising their activity and engage positively with weather services, which was a source of frustration to meteorologists in the 40s.[58] Finally, meteorologists had to demonstrate the economic utility of forecasts. During the 40s, it

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[56] Mark Blaug, "The Formalist Revolution of the 1950s," *Journal of the History of Economic Thought* 25, no. 2 (June 2003): 145–56; Dimitris Milonakis, "Formalising Economics: Social Change, Values, Mechanics and Mathematics in Economic Discourse," *Cambridge Journal of Economics* 41, no. 5 (August 1, 2017): 1367–90.

[57] J. C. Thompson, "A Numerical Method for Forecasting Rainfall in the Los Angeles Area," *Monthly Weather Review* 78, no. 7 (July 1, 1950): 113–24.

[58] Charles C. Bates, "The Status of Applied Meteorology in the United States in the Post-War Period," *Bulletin of the American Meteorological Society* 30, no. 6 (June 1949): 199–203. This thesis suggests why weather services may be more sought after in the 2020s when compared to the 1940s.

seems many meteorologists saw better verification of forecasts as the road to demonstrating usefulness.[59] However, in 1951, H. C. Bijvoet and W. Bleeker of the Royal Netherlands Meteorological Institute demonstrated that sometimes overly pessimistic forecasts were of greater use to industry than more accurate forecasts, providing a basis for economic studies of weather information to chart a course independent of mainstream meteorology. The authors reveal some of their motivation for engaging in such activity: "directors of meteorological services are rather often forced to fight defensive battles for their budgets." Bijvoet and Bleeker were trying to speak on the economist's terms, as it was often economists who held the purse strings.[60] This struggle is reflected in the fact that the idea of weather information having a monetary value was driven by those within national meteorological services.

Bijvoet and Bleeker set off a series of papers in which forecasts were analysed, optimised and valued in the context of idealised economic decision processes.[61] Later, in the 1960s, these meteorologists began to apply forecasts to specific sectors, for example the raisin industry.[62] In addition, the 60s heralded the limited extension of weather aspects into economics literature, beginning with research commissioned by NASA in support of its first weather satellites.[63] However, all of this work was done on the microeconomic scale—considerations of decisions to be made by the individual company or manager dealing with

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[59] Glenn W. Brier and Roger A. Allen, "Verification of Weather Forecasts," in *Compendium of Meteorology* (Springer, 1951), 841–48.

[60] H. C. Bijvoet and W. Bleeker, "The Value of Weather Forecasts," *Weather* 6, no. 2 (1951): 36–39.

[61] J. C. Thompson, "On the Operational Deficiences in Categorical Weather Forecasts," *Bulletin of the American Meteorological Society* 33, no. 6 (June 1952): 223–26; J. C. Thompson and G. W. Brier, "The Economic Utility of Weather Forecasts," *Monthly Weather Review* 83, no. 11 (November 1, 1955): 249–53; J. C. Thompson, "Operations Research Looks at the Weather Forecast," *Weatherwise* 10, no. 5 (October 1, 1957): 149–53; L. E. Borgman, "Weather-Forecast Profitability from a Client's Viewpoint," *Bulletin of the American Meteorological Society* 41, no. 7 (July 1960): 347–56.

[62] L. L. Kolb and R. R. Rapp, "The Utility of Weather Forecasts to the Raisin Industry," *Journal of Applied Meteorology* 1, no. 1 (March 1, 1962): 8–12.

[63] Richard R. Nelson and Sidney G. Winter, "Weather Information and Economic Decisions" (Santa Monica: RAND, August 1, 1960); Richard R. Nelson and Sidney G. Winter, "A Case Study in the Economics of Information and Coordination: The Weather Forecasting System," *The Quarterly Journal of Economics* 78, no. 3 (1964): 420–41.

a single weather variable—which seriously hindered the purpose of promoting weather services as worthy of public support. Indeed, the analytical reductionism employed in this work meant that the incorporation of the complexities of a national economy were almost impossible. However, by the middle of the 1960s, attempts were again being made.[64]

In the UK, Basil John Mason, the director-general of the Meteorological Office opened a 1966 lecture given to the Royal Meteorological Society by pointing out how poorly funded his national meteorological service was when compared to that of the United States. Mason adopts what could be termed as a “back of the napkin” approach to analysis, often extrapolating weather-loss reports from the US industry to the UK equivalents, before calculating a cost/benefit ratio. An obvious (and admitted) weakness of this analysis is that Mason had no data for an industry which operated with no weather service, leading to the basis of many of his calculations being educated guesses. Although he admitted that his calculations were no more than rough estimates, Mason still produced a numerical headline: “I think, however, that my estimates are good enough to show that the economic value of the civil national weather service is at least £50m to £100m per annum, for a cost of £4m, with a probable overall benefit/cost ratio of about 20 to 1.”[65] Mason’s actions had many echoes of those of Reichelderfer in 1940—national weather service leaders using dubious data to make grand pronouncements about the value of their organisations’ outputs.

Simultaneously in New Zealand, PhD student John Maunder used multiple regression techniques in an attempt to measure the financial impact of weather on the country’s vitally important agriculture industry, which at the time was suffering from drought years and dropping wool prices. Maunder employed a climatic dataset from a 27-year time

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[64] Maunder, *The Value of the Weather*, 308–9.
[65] B. J. Mason, “The Role of Meteorology in the National Economy,” *Weather* 21, no. 11 (1966): 393.

period.[66] However, this approach had major problems, as Maunder himself noted two years later "it is very difficult to isolate the contribution made by any one of the various components of the climate such as temperature, day length, light intensity, and precipitation."[67] In addition, Maunder's technique only attempted to measure the value of weather events, not of weather information, which was perhaps less useful for national weather services attempting to justify their existence.

In 1969, the World Meteorological Organisation Commission for Climatology requested Swedish meteorologist Roy Berggren to "summarize information on methods and results of evaluations of economic benefits from the application of climatological information to various activities." His report, published in 1975, emphasised the low cost of climatological studies compared to the gain, providing an overview of weather information as applied to a wide variety of sectors. However, Berggren warns in his introduction that although "it is quite easy to establish that there are certain economic benefits to be derived from using climatological information, […] it is next to impossible to ascertain their precise value." Berggren also makes very clear his distinction between climatological and weather forecasting services, saying "the former usually affects capital investment, whereas the latter often only pertains to operational costs."[68]

By the 1970s the weather economics and its rare surveys began to come under criticism from two different angles which are represented in two reviews for Maunder's *The Value of Weather*.[69] From one side, economist Delbert Ogden lamented the lack of content in the

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[66] W. J. Maunder, "Climatic Variations and Agricultural Production in New Zealand," *New Zealand Geographer* 22, no. 1 (1966): 55–69.

[67] W. J. Maunder, "Agroclimatological Relationships: A Review and a New Zealand Contribution*," *The Canadian Geographer / Le Géographe Canadien* 12, no. 2 (1968): 73–84.

[68] R. Berggren, "Economic Benefits of Climatological Services," Technical Note, WMO Technical Notes (Geneva, Switzerland: WMO, 1975).

[69] Maunder, *The Value of the Weather*.

area.[70] On the side of geographers, Frederick Hare criticised a strictly economic framing to be insufficient to describe the human interaction with an increasingly politicised and valued atmosphere.[71] When it came to individual industries, the analytical approach continued to bear fruit in incorporating the weather factor. However, there appears to have been a disconnect between economically-oriented meteorologists and the industries they investigated. For example, a classic paper by James Mcquigg and Russel Thompson investigating the application of weather information to a gas supply system has been cited plenty of times by fellow applied meteorologists, but appears to have been largely ignored within gas industry literature.[72]

This thesis provides some illumination as to why this has been the case. Extensive research was being done *within* industry on the use of weather information, especially in large centralised industries like those found in the utilities sector. Understanding the value of weather requires not only examining the views and arguments of those who have an institutional intertwining with the providers of weather information but also the arguments of those who *buy* weather information—clients. In fact, the opinions of clients should hold much more weight—there is less incentive for clients to make grand pronouncements about the value of weather services that they pay for. This thesis provides some of those viewpoints within the post-war UK utilities.

The Rise of Commercial Weather Services

This thesis comes at a time when the value of commercial weather services is reaching new heights, making it pertinent to explore how atmospheric information exerts changes upon

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[70] Delbert C. Ogden, review of *Review of The Value of the Weather*, by W. J. Maunder, *Journal of Economic Literature* 11, no. 2 (1973): 586–87.
[71] F. Kenneth Hare, review of *Review of The Value of Weather*, by W. J. Maunder, *Geographical Review* 61, no. 2 (1971): 321–22.
[72] James D. McQuigg and Russell G. Thompson, "Economic Values of Improved Methods of Translating Weather Information into Operational Terms," *Monthly Weather Review* 94, no. 2 (February 1966): 83–87. Citations to this paper were investigated using Google Scholar.

society and vice versa. There has been an increase of interest in the commercial opportunity of meteorological services within both the private and public spheres. David and Stanley Changnon have argued that damaging climate events in the late 80s and 90s, ongoing climate discourse, and the deregulation of important markets have led to firms seeking climate expertise and information. In addition, they argue that the rise of information technology and easily accessible expansive historical climate data, combined with advances in atmospheric science, has aided in the provision of relevant climate information.[73] Samuel Randalls has explored the emergence of weather derivatives in the mid-1990s, which he partly attributes to attempts by energy companies to avoid the highly regulated insurance market.[74] The ascendancy of private sector meteorology was hallmarked by the foundation of an international trade association, the International Association of the Hydro-Meteorological Equipment Industry, in 2002.[75]

Atmospheric information is now a rapidly expanding industry. Richard Pettifer, the General Secretary of PRIMET, a pan-European trade association for meteorological service providers operating in the private sector, estimated in 2008 that the value of weather products in Europe alone, excluding aviation, was $300m.[76] More recent 2015 analysis by the UK's Public Weather Service Customer Group puts the economic value of the UK public weather service likely in excess of £1b per annum.[77] In the summer of 2019, the Meteorological Technology World Expo in Geneva, a showcase of private weather services, was deliberately ran concurrently with the eighteenth Session of the World Meteorological

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[73] David Changnon and Stanley A. Changnon, "Major Growth in Some Business-Related Uses of Climate Information," *Journal of Applied Meteorology and Climatology* 49, no. 3 (March 2010): 325–31.

[74] Randalls, "Weather Profits."

[75] Association of the Hydro-Meteorological Industry, *Information and Member Benefits*, 5th ed. (Association of the Hydro-Meteorological Industry, 2018).

[76] Richard Pettifer, "Towards a Stronger European Market in Applied Meteorology," *Meteorological Applications* 15, no. 2 (June 2008): 305–12.

[77] Mike Gray, "Public Weather Service Value for Money Review" (Public Weather Service Customer Group Secretariat, March 2015).

Organization Congress. Graham Johnson, the managing director of the expo, highlighted how “the co-timing took a great deal of communication and a willingness to compromise on both sides, but I think it’s an excellent example of how the public and private sectors are very much starting to join forces.”[78] This reflects the published views of Alan Thorpe, the former Director-General of the European Centre for Medium-Range Weather Forecasts, and David Rogers of the Global Facility for Disaster Reduction and Recovery of the World Bank, who claim that the reduction in public funds for meteorological research must be partly compensated for and remedied through closer integration with the private sector.[79] In summary, corporate weather services are booming and are increasingly being embraced by global institutions.[80]

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[78] “Meteorological Technology World Expo 2019 Showguide” (UKi Media & Events, 2019), 3.

[79] Alan Thorpe and David Rogers, “The Future of the Global Weather Enterprise: Opportunities and Risks,” *Bulletin of the American Meteorological Society* 99, no. 10 (October 1, 2018): 2003–8.

[80] Robert Luke Naylor, “The Weather Enterprise – a Concept in Need of Historical Analysis,” *Notes and Letters of the International Commission for the History of Meteorology* (blog), May 9, 2022, accessed September 14, 2022, https://meteohistory.org/2022/the-weather-enterprise-a-concept-in-need-of-historical-analysis/.

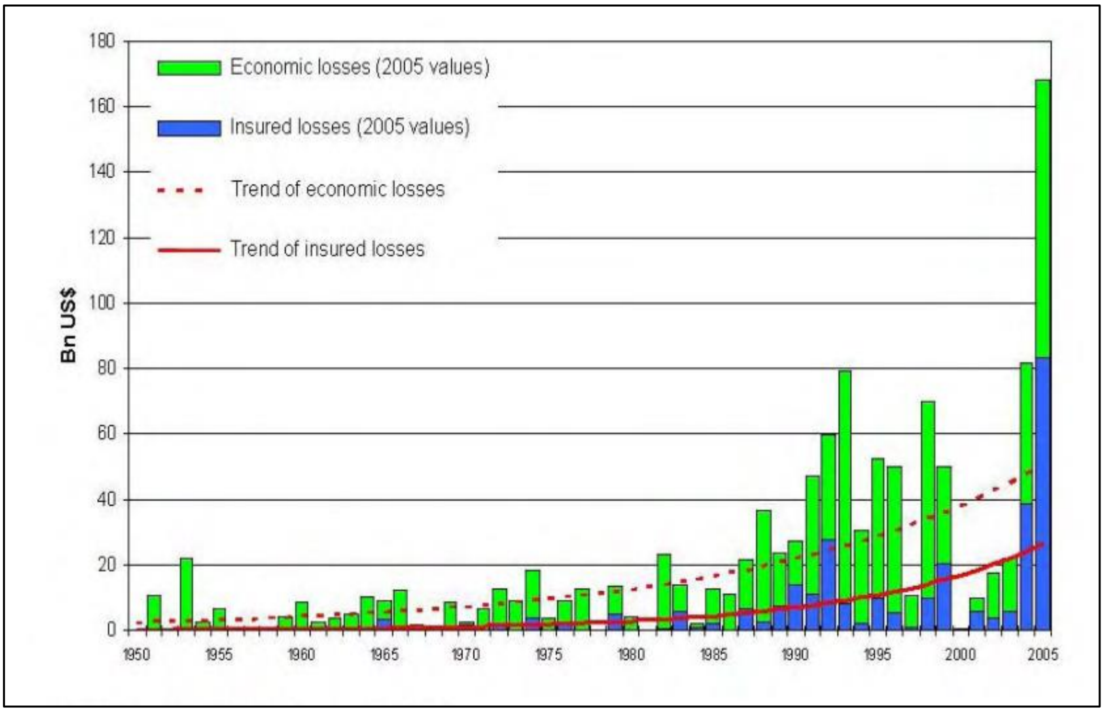

Figure 4. Losses due to "great weather disasters" as reported by the Hohenkammer workshop. Derived from Munich Reinsurance Company data[81]

However, this growing multi-billion-dollar meteorological services industry arises concurrently with increasing weather damages (Fig. 4). A 2007 World Meteorological Organization report claimed that "economic losses from hydrological or meteorological natural hazards are increasingly significant."[82] A 2013 publication from the World Bank agreed, stating that there has been an upward trend in disaster losses since the 1980s.[83] These conclusions were largely based on the data of reinsurance companies, with Munich Reinsurance and Aon Plc claiming trends of increasing weather-related losses.[84] In 2022,

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[81] Peter Höppe and Roger A. Pielke Jr, eds., *Report of the Workshop on "Climate Change and Disaster Losses: Understanding and Attributing Trends and Projections" 25–26 May 2006, Hohenkammer, Germany*, 2006, 5.

[82] C. C. Lam et al., "Guidelines on Capacity Building Strategies in Public Weather Services," PWS, WMO/TD (Geneva: World Meteorological Organization, 2007), 9.

[83] World Bank, "Building Resilience: Integrating Climate and Disaster Risk into Development" (Washington, DC: World Bank, November 2013) , accessed September 14, 2022, https://openknowledge.worldbank.org/handle/10986/16639.

[84] Aon plc, "2021 Weather, Climate and Catastrophe Insight," 2021; Munich Re, "Extreme Weather Risks," 2022, accessed September 14, 2022, https://www.munichre.com/en/risks/extreme-weather.html.

the European Environment Agency website claimed that the average annual inflation-corrected losses from weather and climate-related extremes in EEA countries were around €9.5b in 1981–90, €11.0b in 1991–2000, €13.2b in 2001–10 and €14.5b in 2011–20.[85] These rising damages appear to coincide with rising death tolls from natural disasters, with increasing GNP generally not reducing the number of deaths per capita.[86] Historian of meteorology and climate Vladimir Janković asks how this double growth of weather information and weather losses can occur, and whether it is to do with factors that are internal or external to the economy.[87] Throughout this thesis, I will consider Janković's question with regard to the UK utilities, asking how the increased use of weather information affected the vulnerability of systems to weather and climate events.

The problem of whether commercial climate services have actually led to better decision-making is an important topic in the literature. Drawing on twenty-seven expert interviews, an interdisciplinary group led by Kieran Findlater argue that although climate services promise better decisions, they mainly focus on better data. Problems that Findlater et al. identified included a "narrow economic valuation of products" rather than a broader assessment of how decision-making can be improved, a reliance on broad assumptions regarding demand as opposed to truly being "demand-driven," and a focus on products rather than the processes that result.[88] Such unease on the current model of climate services is also reflected by geographers Sophie Webber and Simon Donner, who argue that there should be a shift away from the commercialised model of climate services to ensure that climate information can consistently be made useful for assisting poorer

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[85] European Environment Agency, "Economic Losses from Climate-Related Extremes in Europe," February 3, 2022, accessed September 14, 2022, https://www.eea.europa.eu/ims/economic-losses-from-climate-related.

[86] Ian Burton, Robert W. Kates, and Gilbert F. White, *The Environment As Hazard*, 2nd edition (New York: Guilford Press, 1993), 12–14.

[87] Janković, "Working with Weather."

[88] Kieran Findlater et al., "Climate Services Promise Better Decisions but Mainly Focus on Better Data," *Nature Climate Change* 11, no. 9 (2021): 731–37.

nations in adapting to climate change.[89] By taking a deep-dive into several examples of how demand for weather and climate information develops and shifts with changes to the wider economy, this thesis provides essential context to such debates on how climate services should be provided, showing to what extent such demand-driven information has truly protected the relevant industries from ostensibly external impactors such as those that might arise from climate change.

Information Transfer and Processing

This thesis explores how information and knowledge was transferred between the Meteorological Office and the electricity, gas, and water industries. Knowledge transfer has become a significant part of organisation studies literature, providing an important conceptual framework through which to see atmospheric information. Frank Blackler conceptualized organisational knowledge as "an active process that is mediated, situated, provisional, pragmatic and contested", criticising previous conceptions of knowledge as a timeless body of truth—a specific entity that is distinct from learning. To Blackler, knowledge could be recast as a phenomenon which: (a) finds form in systems of control, collaboration, technology and language (mediated); (b) is specific to particular contexts (situated); (c) constructed and constantly changing (provisional); (d) problem-oriented (pragmatic); and (e) subject to power relations (contested).[90] This thesis will show how usable weather information took on many of these characteristic within individual industries. For example, usable weather information takes its form through the systems it serves; the relationship between consumer demand and daylight illumination is vitally important for the electricity industry, but is not important at all for the gas industry (few

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[89] Sophie Webber and Simon D. Donner, "Climate Service Warnings: Cautions about Commercializing Climate Science for Adaptation in the Developing World," *Wiley Interdisciplinary Reviews: Climate Change* 8, no. 1 (2017): e424.

[90] Frank Blackler, "Knowledge, Knowledge Work and Organizations: An Overview and Interpretation," *Organization Studies* 16, no. 6 (November 1, 1995): 1021–46.

people use gas lighting in 2020). As will also be shown, weather information is also subject to power relations and can be used be used by dissidents within industries to analyse supply systems and argue for change, as well as by ambitious managers to override the concerns of shift staff.

Scholar of marine transportation Elizabeth McNie researched the transfer of information between organisations under the context of climate-based decision-making. McNie expresses concern that basic-science oriented scientists are producing too much of the "wrong sort" of information which fails to take into account decision-makers' needs. For information to be considered useful it has to satisfy the demands of decision-makers. First, the information has to be salient and relevant to the specific context in which it is needed. Second, the information must be credible i.e. considered accurate, valid, and high-quality by the user. Third, the information must be considered legitimate and free of political bias. McNie outlines several barriers to the production of useful information, such as the cultural gulf between scientific and political systems, a focus on the global rather than the local with regard to information produced for decision-makers, and cultural barriers against policy-oriented research within science itself. McNie concludes that there is much to learn about how information is selected, packaged, presented, and evaluated.[91] This is an area that my thesis, with its historical perspective, could actively contribute to. McNie's analysis mainly orients from the information provider's perspective. There is a need for more work on how the buyers of atmospheric information—the clients—shape this information for their own needs.

This thesis concerns the transfer and processing of weather information within various industries, and several historians of science have considered the transfer and processing of

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[91] Elizabeth C. McNie, "Reconciling the Supply of Scientific Information with User Demands: An Analysis of the Problem and Review of the Literature," *Environmental Science & Policy* 10, no. 1 (February 2007): 17–38.

weather data in an academically oriented context, attacking the stereotype of data as a definitive, static entity. Historian of climate and information structures Paul Edwards has applied a sophisticated circulation framework and coined the term *data friction* for the effort exerted in gathering global weather data, and explores the technological, political and institutional factors that helped or inhibited weather data's free flow. Edwards argues that data standards acted as lubricants of information transfer by reducing variation and complexity in processing of weather data, as well as "black boxing" decisions that would otherwise need to be made. Edwards explores the gargantuan efforts exerted to make complete, coherent and consistent global weather datasets—a complex process requiring sophisticated models of data which eliminate the boundaries between weather data, simulation, and model.[92] Janković has attacked the stereotype of the climate archive being a "stable and definitive" warehouse of raw data, emphasising that "climate as a scientific concept cannot exist prior to data and data prior to archives." He shows how the intended application of the climate data, and feedback from external stakeholders shaped not only how and which data was stored, but metamorphised the climate data itself, as it was continuously improved or changed in order to be made useful. Edwards and Janković have both reconsidered the stereotype of definitive data, showing that weather data's flow, manipulation, analysis, and archiving are essential actors in the history of atmospheric science. This project will use some of this new style of history with regard to the industrial sector, showing how climate data and weather forecasts were metamorphised to become more useful in the electricity and gas industries.

The rise of digital electronic computers has formed an important part of the literature in the history of atmospheric studies. Earlier historiography focused on the contribution of Hungarian-American mathematician and computer scientist John von Neumann, who was a

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[92] Edwards, *A Vast Machine*.

leader within the first project to develop computer-based numerical weather prediction.[93] Writing from a more meteorological perspective, historian of meteorology Kristine C. Harper has argued that the creation of forecast weather maps by computers instead of by hand profoundly changed the discipline. She emphasises how meteorologists as well as computer technicians played a crucial role in developing computer-based weather forecasts.[94] In addition, the introduction of computers to the UK post-war nationalised industries has been subject to much academic discussion. Historian of science John Hendry has shown how the UK government attempted largely unsuccessfully to boost the UK computer industry through encouraging the use of British computers in the nationalised industries.[95] Historian of technology Marie Hicks has examined how the UK government used gender discrimination under the guise of meritocracy to undermine the participation of women in the computer industry, arguing that this presented a stumbling block for the industry's success.[96] In this thesis, I examine the role of the role of the introduction of electronic computers in the incorporation of weather forecasts into the management of the large technological systems of UK nationalised industry, arguing that they had a much less decisive impact than might have been assumed.

Operational Research

Operational research has no agreed upon definition, but became an institutionalised area of research in the mid-20th century through the creation of its own journals, university

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[93] William Aspray, *John Von Neumann and the Origins of Modern Computing* (MIT Press, 1990); Frederik Nebeker, *Calculating the Weather: Meteorology in the 20th Century*, International Geophysics Series ; v. 60 (San Diego: Academic Press, 1995).

[94] Kristine Harper, *Weather by the Numbers: The Genesis of Modern Meteorology*, Transformations (Cambridge, Mass: MIT Press, 2008).

[95] John Hendry, *Innovating for Failure: Government Policy and the Early British Computer Industry* (Cambridge, Mass: MIT Press, 1990).

[96] Marie Hicks, "Meritocracy and Feminization in Conflict," in *Gender Codes*, ed. Thomas Misa (John Wiley & Sons, Ltd, 2010), 95–114.

courses, and learned societies.[97] The build-up to the Second World War accelerated the consolidation of the subject through university researchers being employed to optimise Britain's air defence systems, with historians of science Mike Fortun and Silvan Schweber arguing that physicists and their methods were central to the development of operational research during the war.[98] Broadly speaking, operational research denotes the intersection of the physical science sphere with the management sphere, and has variously (and problematically) been characterised by many early practitioners by the use of the 'scientific method', its usage of mathematical statistics, and the acceptance of probabilities with regard to helping executives make decisions.[99] Regardless of the definition, many of the problems tackled by operational research involved the optimisation of a value (e.g. fuel) under certain parameters and objectives, solving problems in supply chain management, routing, and project planning. Models created in operational research often incorporate a meteorological component, which can be expressed, for example, through the modulation of demand, supply, or delivery speed.[100]

According to economic historians Maurice Kirby and Rebecca Capey, UK operational research found a peacetime home in the National Coal Board (NCB) and the British Steel Industry Research Association (BISRA). The first director of BISRA, Charles Goodeve, had worked with operational researchers during the war and founded an operational research

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[97] The scope of operational research was contested. W. L. Parkinson and David Taylor, an operational efficiency engineer and operational research officer of the Central Electricity Generating Board, claimed in a 1965 publication that operational research had started at the electricity board in 1954, ignoring the fact that power engineer Paul Schiller had produced a review of operational research in the industry in 1951: Paul Schiller, "Operational Research in Electricity Distribution and Utilization. A Review of Progress," *Proceedings of the IEE—Part I: General* 98, no. 112 (July 1951): 229–38; W. L. Parkinson and David Taylor, "Operational Research in the Central Electricity Generating Board," *OR* 16, no. 2 (1965): 133–43.

[98] M. Fortun and S. S. Schweber, "Scientists and the Legacy of World War II: The Case of Operations Research (OR)," *Social Studies of Science* 23, no. 4 (1993): 595–642.

[99] Maurice W. Kirby, *Operational Research In War And Peace: The British Experience From The 1930s To 1970* (London; River Edge, NJ: Imperial College Press, 2003).

[100] For example: H. G. Berrisford, "The Relation between Gas Demand and Temperature: A Study in Statistical Demand Forecasting," *OR* 16, no. 2 (1965): 229–46.

group within BISRA in early 1947. This group expanded from a staff of two in 1947 to more than fifty in the mid-1960s, working on problems such as the optimisation of port operations and the calculation of optimal repair programmes for furnaces. Likewise, a similar group within the NCB, established in 1948, worked on problems regarding the efficiency of haulage, communications, and tunnelling underground. By the mid-1960s, operational research had proliferated within most sectors of the UK economy, including the gas and electricity industries.[101] Many of the individuals who pushed weather-optimisation within the UK utilities industries were strongly affiliated with the operational research community, a subject that lent academic prestige to a certain school of operational management.[102]

There is a need for a post-war history of atmospheric information that is oriented towards the priorities and operational procedure of clients. By drawing on archival material from the industries themselves, this project will be able to better understand when, how, and why atmospheric information became ever relevant to the wider economy outside of meteorological and academic circles during the post-war period. Crucially, this project will not start on the assumption that weather information is a static commodity which is exclusively created within the confines of meteorological institutions, rather that weather information is an active process that is situated, provisional, pragmatic and contested. Rather than seeing the clients of weather information as passive receptacles, this history will examine more closely how weather information resonated (or did not resonate) with the specific technological, economic, and political needs of diverse industrial actors. In doing so, this thesis will attempt to unpack the complex reciprocal interaction between the

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[101] Maurice W. Kirby and Rebecca Capey, “The Origins and Diffusion of Operational Research in the UK,” *Journal of the Operational Research Society* 49, no. 4 (April 1, 1998): 307–26.

[102] Schiller, “Operational Research in Electricity Distribution and Utilization. A Review of Progress”; H. G. Berrisford, “The Relation between Gas Demand and Temperature: A Study in Statistical Demand Forecasting,” *Journal of the Operational Research Society* 16, no. 2 (June 1, 1965): 229–46; Frank Lyness, “O.R. and U.K. Natural Gas Depletion Strategy,” *European Journal of Operational Research* 2, no. 3 (May 1978): 160–67.

atmosphere and industry, understanding how the atmosphere came to affect the operational procedure of industry and how changes within industry affected its sensitivity and need for this information.

Notes on Sources

As a client-oriented history that centres industry personnel as the main actors, this project makes use of industrial archives. Most unpublished material on the electricity industry comes from the extensive electricity collection of the Science and Industry Museum, Manchester. This material originates from the Electricity Association, formerly the Electricity Council, the governmental body that oversaw the coordination and regulation of the electricity industry from 1958 to privatisation in 1989–90. In practice the Electricity Council became the information repository for much of the industry, meaning the archive's material extends far beyond the activities of the Council itself. In the leadup to privatisation, the Council lost its archive-keeping responsibilities, meaning the collection was transferred to the Science and Industry Museum in two instalments 1989–90. The material covers a wide time period stretching from the late 19th century to the early 1990s and coverage includes the development of the nationalised industry in the post-war period.[103] Of particular use to this project are unpublished internal research papers, meetings proceedings, and communications between the industry and the Ministry of Power that reveal why politicians took an occasional interest in weather and climate information.

Unpublished material on the gas industry mostly comes from the National Gas Archive based in Warrington. This archive operates as a partnership between the multinational electricity and gas utility company National Grid plc and the North West Gas Historical

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[103] Elizabeth Sprenger and Pauline Webb, "Persuading the Housewife to Use Electricity? An Interpretation of Material in the Electricity Council Archives," *The British Journal for the History of Science* 26, no. 1 (1993): 55–65.

Society, a non-profit group of former gas industry employees. Based on official stamps left on the documents, it can be inferred that the National Gas Archive took material from the full range of libraries within the nationalised industry, including those of the Area Boards, research stations, and Gas Council. This archive was especially useful for the internal reports of the nationalised gas industry's institutions, including the Gas Council and the British Gas Corporation that superseded it.

Offline sources regarding the water industry came from the National Library of Scotland, the National Archives at Kew, and the Manchester Archives Local Studies. The Journal of the Institution of Water Engineers and its successors formed a crucial source base for this thesis, and the National Library of Scotland held the full collection of undigitized pre-1987 material. The National Archives at Kew held information on the national bodies that were founded after the water industry was reorganised in the 1970s—most important for this project were the reports of the Central Water Planning Unit, a quango created around 1973 to advise on industry planning. The Manchester Archives Local Studies held operational archival material for the Bolton Corporation Waterworks, which give a snapshot into how weather and climate information were being used day-to-day in the immediate post-war period.

Online sources for primary information for all chapters include the online collection of the Meteorological Library which includes the annual reports of the Meteorological Office and the British Rainfall Organisation. The online collection of reports from the industry-wide research body UK Water Industry Research Ltd was invaluable for examining the more recent history of the water industry. The period covered by this thesis makes published primary sources affordable to purchase online in physical form, the most fruitful of which were the operational manuals written by engineers, most notably the Central Electricity Generating Board's "Modern Power Station Practice" series and the Institution of Water

Engineers and Scientists' "Water Practice Manuals." I was also able to pick up the British Gas Corporation's book *Gas Making & Natural Gas* (1972), which outlines the industry's operational procedure before and after the natural gas transition.

Established histories of the UK electricity, gas, and water industries were essential for this project. For the electricity industry, I made extensive use of economic historian Leslie Hannah's *Electricity Before Nationalisation: A Study of the Development of the Electricity Supply Industry in Britain to 1948* (1979) and his later work *Engineers, Managers and Politicians: Electricity Supply Industry in Britain from 1948 to the Present* (1981). For the gas industry, I used historian of science Trevor Williams's *A History of the British Gas Industry* (1981). For water, I often consulted John Hasan's *A History of Water in Modern England and Wales* (1999). All four of these works played an important role in framing this thesis, allowing developments in the processing of atmospheric information to be placed within broader contexts.

Chapter Outline

The remaining chapters of this thesis are oriented around three key case-studies in the post-war UK utilities. The second chapter explores the incorporation of formal atmospheric information into the UK electricity grid. This process began in earnest during debates regarding the direction of the electricity industry around and during the Second World War, when a small group of power engineers argued that the industry had to limit its own expansion in order to avoid system failure. This group used climate information in an attempt to strip out the weather-based variability in demand data in order to analyse changing demand patterns without this random component. Much of this same work was later utilized during a time of post-war shortage of material to increase efficiency, with electricity board staff taking time to research the relationships between weather and demand in order to inform the scheduling of power generation. Finally, with an increase in interest in indicative planning within government, we see climate information used to inform long-term demand forecasts within industry. In this chapter, it is established that crucial atmospheric study existed outside the meteorological community, and that these studies were motivated by changes to the national economy.

The third chapter looks at the use of atmospheric information in the gas industry. Unlike the electricity industry, the gas industry went through two technological transformations in the period 1945–75. Firstly, in the 1950s and 60s, coal-based gas manufacturing processes were replaced by new oil-based processes that contributed to the rationalisation and centralisation of the industry. Secondly, and most importantly, the discovery of North Sea Gas in 1965 led to a complete system transformation, with the rapid construction of National Transmission System that delivered gas across the country from a small number of terminals connected to the North Sea platforms. In the second case especially, this system transformation made the industry more sensitive to the weather, with the nationalised supply industry being contractually obliged to provide accurate weather-based demand forecasts to North Sea gas producers. As a result, individuals within the industry worked to create a nationally standardised format for Meteorological Office forecasts. In addition, the construction of a whole new distribution system required careful consideration of storage requirements for offsetting weather-induced demand fluctuations, leading to industry researchers investigating long-term climate information in order to minimise construction expenditure. This chapter clearly demonstrates how technological transformation can in fact make critical infrastructure more weather sensitive, not less, and how industry workers used atmospheric information to react to emergent needs.

The use of atmospheric information by the water industry is the subject of the fourth chapter, and expands on the previous two chapters by examining a fundamental supply dependence on the atmosphere as well as a demand dependence. Prior to the 1970s, water engineers were mostly interested in the longest rainfall datasets that they could acquire, as these were seen as indicators of the "true" climate that best informed expansions to the supply system in order to support wider industrial expansion. Centralisation and industry cuts in the 1970s and 80s respectively focused minds on efficiency, and several industry researchers considered using weather information to minimise the pumping of water, although it appears that these models were never used in practice. In the 1990s, under regulatory pressure, the water industry incorporated climate change into its long-term demand forecasts. The water industry shows how conceptualisations of the atmosphere changed with economic changes, as interest shifted from the longest-term climatic datasets to short-term weather forecasts and finally to climate change.

Chapter Two—Working on the Atmosphere's Frequency: Atmospheric Information in the UK Electricity Boards

Electricity represents a vitally important supply that underpinned post-war economic expansion in the UK. In 1963, an equivalent of 10% of total UK capital expenditure went into the industry, which since April 1948 had been fully nationalised under successive electricity boards.[1] This investment was required in an attempt to facilitate a strong growth

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[1] Cecil T. Melling, "Long Term Planning for Electricity Supply" (Electricity Council, November 1963), 2, ESI collection box 433, Science and Industry Museum. Since the first establishment of electricity networks in the nineteenth century, there was a recognition that larger networks provide a cheaper service through economies of scale. As the twentieth century began, increasing demand for electricity and international rivalry brought the issue into the political spotlight. As shown by Leslie Hannah, the complex struggles of linking up regional, often privately controlled, electricity networks led to the foundation of the government-controlled Central Electricity Board in 1927. The Central Electricity Board instituted what eventually became an integrated national electricity distribution network that linked up important generating stations with existing regional networks through seven regional control centres, which were in themselves linked up in 1938. However, generation and local distribution were still largely handled by private companies or municipal government (collectively known as undertakings): Leslie Hannah, *Electricity Before Nationalisation* (Springer, 1979). April 1948 as part of a wave of nationalisations under Clement Attlee, the entire electricity industry was fully

in demand that was more or less consistent for the first two post-war decades, with demand more than tripling between 1948 and 1963.[2] The nationalised electricity industry represented an important client for the Meteorological Office. In a 1960 internal report, James Stagg, the Meteorological Office's director of services, described the electricity board as "the largest public utility customer of the office," going on to say that the methods of electricity distribution control employed by the board depended "to a large extent" on the Meteorological Office's weather forecasts.[3] This importance was reflected by views within the electricity industry. In 1974, the electricity board's chief load (i.e. demand) forecaster Colin Barnett wrote that the economic planning and operation of the electricity supply system was "dependent" upon forecasting the variation and growth of demand, and that "the erratic behaviour of weather" accounted for practically all of the variability.[4]

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nationalised, taking all former undertakings under government ownership. The newly founded British Electricity Authority oversaw the regulation, policy, generation and transmission of electricity, and sold electricity to fourteen Area Electricity Boards for distribution. The number of Area Electricity Boards was reduced to twelve when the British Electricity Authority was replaced by the nearly identical Central Electricity Authority in April 1955. In January 1958, the responsibilities of the Central Electricity Authority were split between two newly founded institutions—the Central Electricity Generating Board and the Electricity Council. The Central Electricity Generating Board took over the generation, transmission and sales responsibilities of the Central Electricity Authority, and the Electricity Council took over the regulatory and policy function: Leslie Hannah, *Engineers, Managers and Politicians: Electricity Supply Industry in Britain from 1948 to the Present*, First (London: Palgrave Macmillan, 1982). It should be noted that from 1955 in Scotland generation was the responsibility of the South of Scotland Electricity Board and the North of Scotland Hydro-Electric Board, that were separate from the Central Electricity Generating Board. This structure of the industry lasted until the early 1990s, when the Central Electricity Generating Board was split up and privatised piecemeal by successive Conservative governments, with the Electricity Council and Central Electricity Generating Board formally winding down in 2001. The Central Electricity Generating Board was split into three generating companies, fourteen regional electric companies and a single system operator (National Grid Electricity System Operator Limited as of 2020). The new regime was dictated by a document known as the Grid Code, which regulates the relationship between these privatised components: National Grid Electricity System Operator Limited, "The Grid Code," May 7, 2020. For the purposes of this chapter, the Central Electricity Board, British Electricity Authority, Central Electricity Authority, and Central Electricity Generating authority will simply be referred to as "the electricity board."

[2] Hannah, *Engineers, Managers and Politicians*, 290–91.

[3] J. M. Stagg, "Report on the Organisation of the Forecasting Services of the Meteorological Office" (Meteorological Office, 1960), 12–13, AIR 2/14739, National Archives at Kew.

[4] Colin Barnett, "Demand Analysis and Forecasting at the CEGB National Control Centre" (Conference on Load Forecasting, Horsley Towers, 1974), 1. Found in: ESI collection box 400, Science and Industry Museum.

The centrality of demand forecasting to the electricity supply system is explained in an electricity board textbook from 1971. The system (which consisted of power stations, transmission lines, and switching and transforming stations) was interconnected across the UK, pooling generating resources. This meant that national controllers could fully utilize power stations with low production cost (which depended on both the age of the station and the type of fuel used) and restrict the use of stations with high production cost to periods of peak demand.[5] In effect, this meant that even a small margin of error in demand forecasting had damaging consequences for the electricity board. If the forecast were short of actual demand, board managers would have ministers breathing down their necks due to power cuts. If the forecast were higher than actual demand, the least efficient power stations in the country would be left running uselessly, consuming valuable coal that was in short supply in post-war Britain. In addition, electricity generating facilities take time to bring to full capacity, meaning that forecasts are essential for timely responses to changes in demand for electricity. This chapter accounts for the development of a vital stream of information for an industry that was central to UK industrial policy.

I examine how the weather factor was incorporated into UK electricity demand forecasting, a process that began with intuitive interpretation of the sky by local dispatchers in the 1920s, transitioning to the systematic processing of Meteorological Office weather forecasts by the end of the 1950s, until becoming a mostly automatic process by the early 1970s with the use of a series of computer programs. The bases for these forecasts were daily demand curves that depend on the day of the week, the time of the year, and whether the day was a holiday such as Christmas. These set curves were modified for forecasting purposes using weather adjustment techniques; wind and rain strip heat from houses, clouds make rooms darker, low temperatures outside eventually lead to low

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[5] Central Electricity Generating Board, *Modern Power Station Practice: Operation and Efficiency*, 2nd ed., vol. 7 (Pergamon Press, 1971), 290.

temperatures inside. As will be shown, the industry spent much time and effort translating Meteorological Office weather variables into new variables that corresponded with how the weather was responded to through switching on lights or heating. In addition, long-term demand forecasts were needed to inform the construction of new generating plant. These long-term forecasts were mostly dictated by trends in the national economy, but were also normalised using a value known as Average Cold Spell Demand—the demand that the average year would have a 50% chance of exceeding due to weather conditions. The development of this standard required the use of climate information by those within the industry. This chapter explores the political, economic, and technological drivers of the incorporation of the atmosphere into electricity demand forecasting.

This chapter will argue that the incorporation of weather forecasts into the UK electricity distribution system was mainly motivated by several “capacity crises” that plagued the electricity industry from the closing stages of the Second World War to the mid-1960s, when the UK’s capacity to generate electricity was insufficient to meet demand. These crises were caused by a combination of factors, including a war-induced shortage of material for building new generating capacity, an increase in demand for electric space-heating, and an expansionist mantra within the industry that opposed any discouragement of rising demand. This chapter will show how in 1945 Paul Schiller, a dissident within the industry who advocated for demand controls, created and used weather information as a diagnostic tool to closely scrutinise the system load and argue for a change in strategic orientation of the industry towards a more conservative approach, inadvertently assisting the refinement of weather adjusting techniques in the process. In 1952, after a series of disastrous winters in the late 1940s that highlighted the reality of the first capacity crisis, the government published an in-depth report that highlighted the capacity crisis and advocated for the more efficient use of fuels (such as coal in coal-fired power stations). This resonated with weather adjustment techniques, and by 1958 Maurice Davies, an employee of the electricity board, developed a new mathematical treatment of Meteorological Office weather forecasts for load forecasting purposes, the methods of which remained largely unchanged for at least four decades. The use of long-term climate information, however, mainly resulted from a shift within government. Around 1960, a move towards indicative planning within the second Macmillan government coincided the adoption of an officially defined Average Cold Spell demand to standardise planning within the electricity industry, meaning that longer-term climate emerged as an important planning variable. This chapter argues that it was the economic context, not technological advance or particularly cold winters, that drove the use of atmospheric information within the electricity industry.

Weather and Load Forecasting: A Relationship Born in Wartime

Prior to the Second World War, there is little evidence that weather received any kind of systematic numerical treatment when forecasting daily electricity demand, although there is evidence that power engineers were on the lookout for short-term meteorological forecasts that could assist their plant scheduling. Regional network controllers (known as load dispatchers) took an interest in the weather with regard to the day-to-day running of grids. Load dispatchers made their own, often quite intuitive, meteorological observations that were combined with other factors in order to forecast load.[6] Load forecasting required an in-depth knowledge of societal routine as well as an intuition that came with experience; load dispatchers in Manchester were especially mindful of weather on Mondays, as it was the traditional washday and the spike of load demand from electric irons depended on whether clothes were dried inside or outside.[7] In the interwar period load dispatchers made use of direct meteorological observations rather than

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[6] J. S. Forrest, "The Effects of Weather on Power System Operation," *Quarterly Journal of the Royal Meteorological Society* 71, no. 309–310 (1945): 301, 308–9.

[7] Hannah, *Electricity Before Nationalisation*, 125.

meteorological forecasts. At a meeting held in October 1945, E.[8] Powell, a load dispatcher for a London undertaking, explained why Meteorological Office forecasts were insufficient for his needs in 1928: "…[We] found that, although the information was very useful for forecasting the weather conditions two or three days ahead, it did not, unfortunately, give us hour-to-hour forecasts."[9] Regional load dispatchers were looking for short-term weather forecasts—a service that they were unable to obtain from the meteorological community before the war.

The Second World War expanded the role of the Meteorological Office in many different areas of the national economy, and also, through its military role, demonstrated itself to be an important organ of government. On occasion Meteorological Office forecasts had a decisive influence during pivotal moments, for example by delaying the allied landings in Normandy by a day in order to avoid stormy weather.[10] Other contributions are more obscure and esoteric. An example is Operation Outward, a successful attempt to disrupt German infrastructure by sending over unmanned weather balloons on prevailing winds that trailed long wires in order to short-circuit power lines.[11] Operation Outward required collaboration between the meteorological and electricity research communities, a spirit that would linger on for some years after the war through joint conferences and workshops

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[8] First name unknown

[9] Forrest, "The Effects of Weather on Power System Operation," 301–2. Economic historian Leslie Hannah shows how the complex struggles of linking up regional, often privately controlled, electricity networks led to the foundation of the government-controlled Central Electricity Board in 1927. The Central Electricity Board instituted what eventually became an integrated 132kv national electricity distribution network (gridiron) that linked up important generating stations with existing regional networks through seven regional control centres. However, generation and local distribution were still largely handled by private companies or municipal government (collectively known as undertakings) until full nationalisation in 1948: Hannah, *Electricity Before Nationalisation*.

[10] James Rodger Fleming, "Sverre Petterssen, the Bergen School, and the Forecasts for D-Day," *History of Meteorology* 1, no. 1 (2004): 75–83.

[11] Raoul E. Drapeau, "Operation Outward: Britain's World War II Offensive Balloons," *IEEE Power and Energy Magazine* 9, no. 5 (September 2011): 94–105.

before being depressed by Meteorological Office commercialisation and the expansion of research areas within the nationalised electricity industry.[12]

One of the areas that the wartime Meteorological Office expanded into was the incorporation of weather information into electricity demand forecasting, although until 1944 load dispatchers had to use intuition to interpret what the meteorological forecasts meant for electricity demand. Due to wartime national security concerns, weather forecasts were no longer available in newspapers or broadcast by the British Broadcasting Corporation. The Meteorological Office still published the *Daily Weather Report*, but the forecasts were out of date by the time that electricity undertakings received the physical copies. In May 1940, it was agreed that weather forecasts could be couriered from the Meteorological Office to the electricity board. To increase speed, coded daily forecasts began to be telephoned to the electricity board national control centre each morning by December 1942.[13] These forecasts can be assumed to follow the model of the *Daily Weather Report*. For example, the following encompasses the specific forecast for N.W. England for the 24 hours following 12 noon on the January 1, 1940, issued at 11am on the same day[14]:

> Wind southeast, moderate to fresh; fine; low day temperatures; frost at night

Although to the untrained eye this forecast appears to be qualitative in nature, much of the information is in fact quantitative. For example, “moderate to fresh” means that the windspeed would be between 7.5 and 10 meters per second. The forecast was

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[12] Robert Luke Naylor, “John Samuel Forrest: The Power Engineer Who Helped Found Weather,” *Royal Meteorological Society History Group Newsletter* 2021, no. 1 (2021): 4–7.
[13] J. M. Walker, *History of the Meteorological Office* (Cambridge ; New York: Cambridge University Press, 2011), 286.
[14] N. K. Johnson, “The Daily Weather Report of the Meteorological Office, London” (London: Air Ministry, Meteorological Office, January 1, 1940), 2, Met Office Digital Library and Archive.

accompanied by a synoptic weather chart (Fig. 5) that portrayed the observed conditions at 7am, as well as barometric changes between 4am and 7am. It can be seen that from 1940 substantial quantitative weather information was being delivered to the electricity board from the Meteorological Office. However, until 1944 it appears that load forecasters still had to use intuition to interpret the weather forecasts for load forecasting purposes—at this point there were no formal mathematical techniques for translating weather variables into system load.

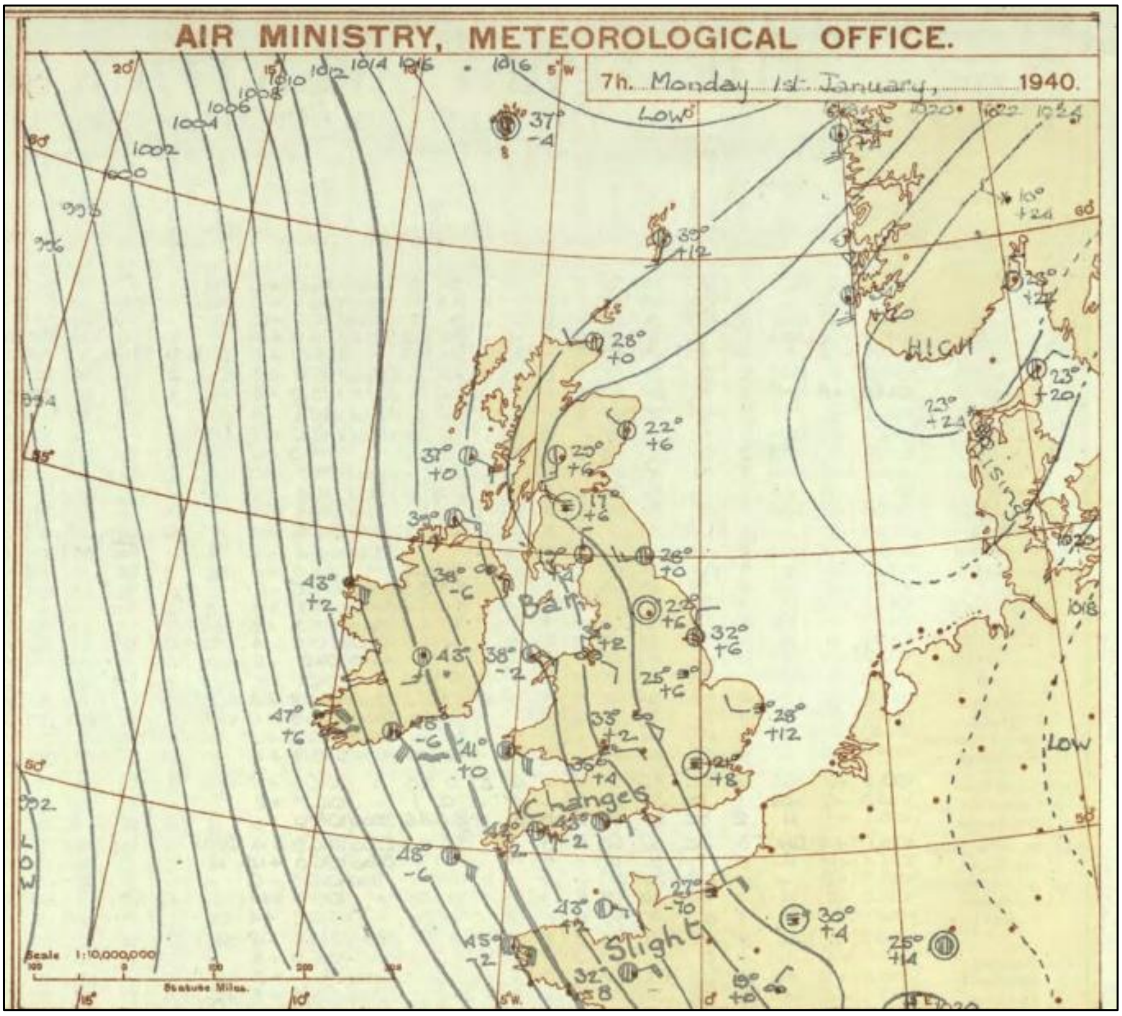

Figure 5. Synoptic weather chart of the British Isles at 7am on January 1, 1940. Isobars are drawn at two millibar intervals. Temperatures are in degrees Fahrenheit. The barometric change between 4am and 7am is written beneath the temperature. The arrows denote the wind direction and speed. The circles indicate a weather station, and the content of the circles is indicative of cloud cover.[15]

Increased interest in quantitative weather-based load forecasting was accompanied by the changing fortunes of the electricity industry, as wartime shortage contributed to a greater concern for efficiency. At the beginning of the war, demand for electricity in the UK slacked off due to blackouts and the halting of civilian industry. As the war progressed, generating plant came in short supply across the war-stricken world as personnel and material were drained into the direct war effort and later reconstruction. This pressure was compounded

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[15] Johnson, 2.

by electricity-intensive armament manufacture and, later, a post-war taste for electric heaters.[16] In the UK, the issue was further accentuated by concerns over the supply of coal, which remained the major fuel source for electricity generation. In July 1944, Minister for fuel and power Gwilym Lloyd George wrote “The effective use of fuels of every kind is of vital importance now, and will continue to be essential to the country’s well-being as long as we are dependent on coal for our heat and power.”[17] UK generating plant remained insufficient until the mid-1950s, leading to frequent load shedding, representing the first capacity crisis for the industry.[18] It is in this environment of shortage that we see an increase of interest in creating more quantitative weather-based load forecasts.

However, one of the sparks for incorporating weather information into electricity demand forecasting came from overseas. In June 1944, Henry Dryar, the chief load dispatcher of the Philadelphia Electric Company, presented what would become an internationally influential paper for the incorporation of weather into load to a meeting of the American Institute of Electrical Engineers. Dryar outlined a basic mathematical method, used within the company since 1939, that identified trends between weather datasets and system load, allowing for load forecasts to be made from meteorological forecasts.[19] Firstly, Dryar split the electrical load into three components—a “base” load that reflected business activity and the seasonal cycle, a variable load that reflected weather, and an erratic load that was caused

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[16] Hannah, *Electricity Before Nationalisation*, chap. 9; Anna Carlsson-Hyslop and Peter J G Pearson, “How Did the Electrical Development Association Attempt to Mould Domestic Electricity Demand in Britain, 1945–1964?,” Working Paper, March 2013.

[17] Fuel Efficiency Committee of the Ministry of Fuel and Power, *The Efficient Use of Fuel: A Text-Book on Fuels and Their Efficient Utilisation for the Use of Students and Technical Men in Industry* (H.M. Stationery Office, 1944), ii–iv.

[18] Dannis Bellamy, “Load Factor in the Electricity Supply Industry” (Leeds: The Yorkshire Electricity Board, July 1958), 12, ESI collection box 434, Science and Industry Museum; Hannah, *Engineers, Managers and Politicians*, chap. 3.

[19] Henry A. Dryar, “The Effect of Weather on the System Load,” *AIEE Transactions* 63, no. 12 (December 1944): 1006–13. These techniques were developed at a time of huge industrial expansion in the US due to rearmament. This expansion put strain on the electricity supply system: Nicholas B. Wainwright, *History of the Philadelphia Electric Company, 1881–1961.* (Philadelphia, 1961), chap. 18.

by unusual events like sports matches. Dryar’s method was to assign weights to three weather variables taken from National Weather Bureau data—temperature, wind velocity, and cloudiness—and use a “cut and try” method to ascertain the correct weights and base load, knowing that the base load should be the same for a particular hour in the week at a similar time of year (Fig. 6). A forecast system load could be calculated by summing up the weather weights based on a meteorological forecast, then making a very simple calculation using the weather weight and the base load.

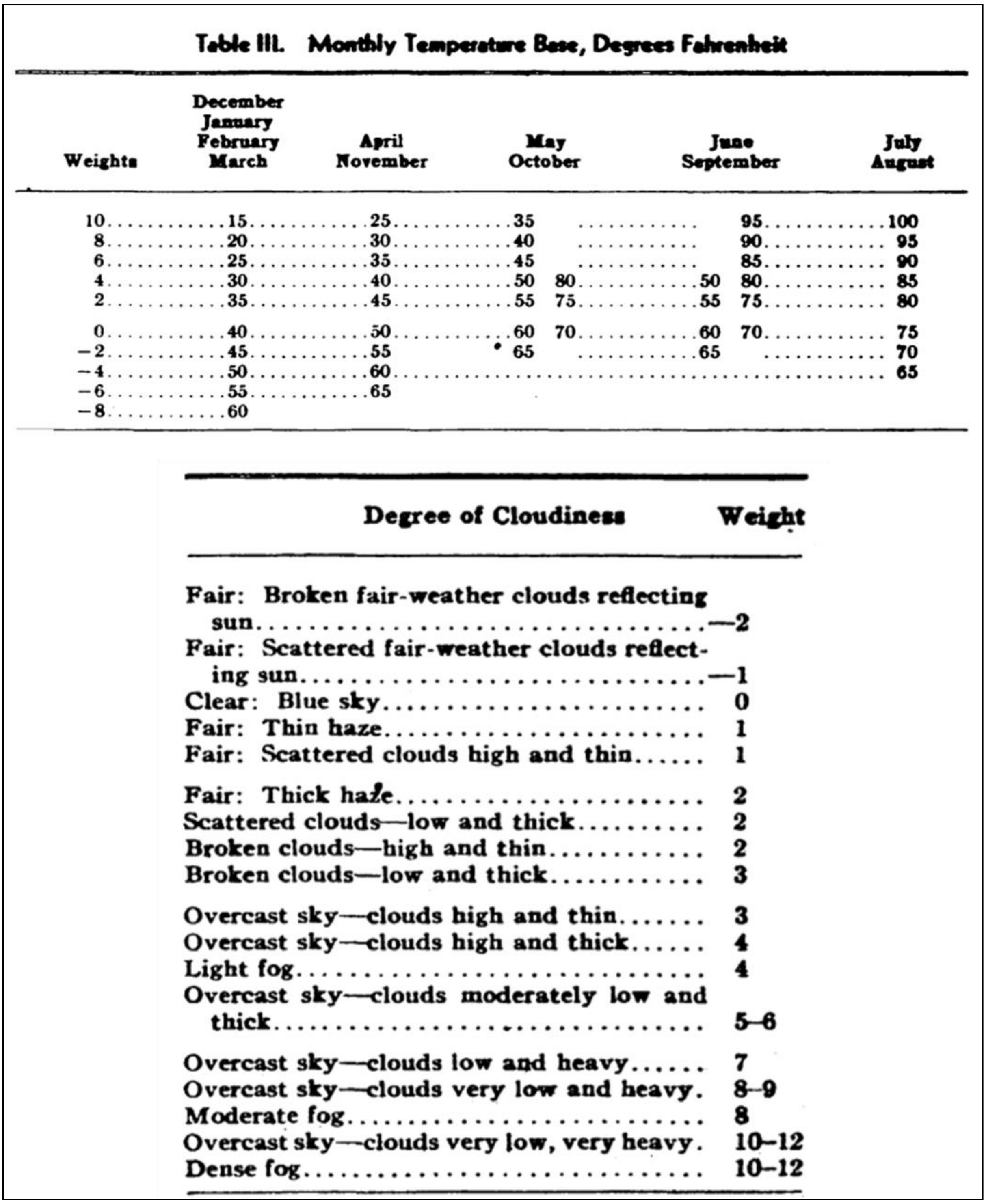

Table III. Monthly Temperature Base, Degrees Fahrenheit

Weights	December January February March	April November	May October		June September		July August
10	15	25	35			95	100
8	20	30	40			90	95
6	25	35	45			85	90
4	30	40	50	80	50	80	85
2	35	45	55	75	55	75	80
0	40	50	60	70	60	70	75
−2	45	55	65		65		70
−4	50	60					65
−6	55	65					
−8	60						

Degree of Cloudiness	Weight
Fair: Broken fair-weather clouds reflecting sun	—2
Fair: Scattered fair-weather clouds reflecting sun	—1
Clear: Blue sky	0
Fair: Thin haze	1
Fair: Scattered clouds high and thin	1
Fair: Thick haze	2
Scattered clouds—low and thick	2
Broken clouds—high and thin	2
Broken clouds—low and thick	3
Overcast sky—clouds high and thin	3
Overcast sky—clouds high and thick	4
Light fog	4
Overcast sky—clouds moderately low and thick	5–6
Overcast sky—clouds low and heavy	7
Overcast sky—clouds very low and heavy	8–9
Moderate fog	8
Overcast sky—clouds very low, very heavy	10–12
Dense fog	10–12

Figure 6. The weights of cloudiness and temperature found under Dryar's "cut and try" method. In addition, a weight of two was assigned for each five miles per hour of wind velocity.[20]

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[20] Dryar, "The Effect of Weather on the System Load," 1007, 1009.

The electricity board received Dryar's paper and, as a result, the board began to institute weather adjusting techniques in late 1944. This was a major development as, for the first time, the board was able to use numerical methods to forecast load. However, the rollout of the new method was initially limited to the non-industrial St Paul's grid control area in late 1944, where forecasting had proved impossible via "ordinary projection methods"[21] (presumably based on data provided by industry), only being used universally by the board in 1949. This limited initial rollout may reflect two factors. Firstly, although by 1944 the first capacity crisis was already inevitable, the manifestation of this fact was covered by the drop in industrial demand immediately following the war, meaning the drive of efficiency within the board was not yet desperate. Secondly, weather-based load forecasts were mostly concerned with domestic load. In 1943, the share of electricity sales for domestic purposes was 21%. By 1948, this share had increased to 35%. Although in 1944 it may have made sense for electricity board planners with limited personnel to restrict weather-based load forecasts to non-industrial areas, by 1949 this position was untenable. The initial rollout of Dryar's method in the UK coincided with the first specialised forecasts for the industry from the Meteorological Office in January 1945, telephoned to the electricity board's National Control Engineer every evening at 8pm to give notice of the conditions the following morning at 8am. The forecasts for the morning weather were especially useful as wartime conditions meant that peak demand for electricity had shifted from the afternoon to the morning.[22]

Dryar's paper was also influential within UK electricity research. The Electrical Research Association's Paul Schiller referenced Dryar in his own work regarding electricity demand, using weather information to analyse the system load and argue for a change of strategic

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[21] Barnett, "Demand Analysis and Forecasting," 1.

[22] Walker, *History of the Meteorological Office*, 286; Hannah, *Electricity Before Nationalisation*, 428.

direction in the industry.[23] At the time, the electricity industry exhibited a messianic drive towards and all-electric future throughout the mid-twentieth century; an expansionist ethos that suppressed domestic electricity prices as well as research into realistic costings. Schiller was somewhat of a political outlier within the UK electricity industry in arguing for restraint in encouraging demand for electricity, even controversially arguing for centralised demand control in a 1941 paper.[24] Paul Schiller was a refugee from the Nazis, and appears to have had a level of technical education that went beyond many of his colleagues in the industry, which he later described disparagingly as "men who are proud to have learnt the trade the practical way—by trial and error—who do not believe in 'theorists', economists, etc."[25] Across industries after the war, this attitude was common amongst those who identified with the developing discipline of operational research. Schiller himself published a 1951 paper reviewing the "progress" of operational research within electricity distribution.[26]

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[23] The Electrical Research Association (officially the British Electrical and Allied Industries Research Association) was founded in 1920, funded jointly by the UK electricity industry and government. In the opening decades of twentieth century British industry came under increased pressure from government and public opinion to invest in research, as UK firms were perceived to be falling behind American and German competition. In response, several co-operative industrial research associations were formed, allowing companies to pool their resources to meet technical challenges. Amongst these was the Electrical Research Association: Ian Varcoe, "Co-Operative Research Associations in British Industry, 1918–34," *Minerva* 19, no. 3 (1981): 433–63. The Electrical Research Association mostly circulated its research through technical reports, although after its first decade it increasingly made use of journals to reach a wider audience. Schiller later identified with the field of operational research: Paul Schiller, "Operational Research in Electricity Distribution and Utilization. A Review of Progress," *Proceedings of the IEE—Part I: General* 98, no. 112 (July 1951): 229–38. Operational research has no agreed upon definition, but became an institutionalised area of research in the mid-20th century through the creation of its own journals, university courses, and learned societies. The scope of operational research within the electricity board was contested. W. L. Parkinson and David Taylor, an operational efficiency engineer and operational research officer, claimed in a 1965 publication that operational research had started at the electricity board in 1954, ignoring the fact that Schiller had produced a review of operational research in the industry in 1951: Parkinson and Taylor, "Operational Research in the Central Electricity Generating Board."

[24] Hannah, *Electricity Before Nationalisation*, 203; Paul Schiller, "The Control of the Domestic Load," *Journal of the Institution of Electrical Engineers—Part II: Power Engineering* 88, no. 5 (October 1941): 373–89.

[25] Martin Chick, *Electricity and Energy Policy in Britain, France and the United States Since 1945* (Edward Elgar Publishing, 2007), 75; Hannah, *Engineers, Managers and Politicians*, 86.

[26] Schiller, "Operational Research in Electricity Distribution and Utilization. A Review of Progress."

However, the divide between Schiller and his colleagues was already clear in 1941. In response to Schiller's 1941 paper that argued for centralised demand control, power engineer Edgar Banner wrote pointedly: "I find the paper disconcerting, as its theme is that the all-electric house is not a desirable object."[27] This criticism was not so much a piece of constructive feedback, more a cry of betrayal. Later, in 1943, Schiller turned his attention to tariffs to encourage restraint, arguing for a shift towards larger standing charges (charges not dependent on a consumer's actual consumption of electricity) to reflect the fact that generating plant was no longer getting cheaper due to economies of scale and that consumers were increasingly using electricity for space heating, an activity that Schiller saw as particularly burdensome in increasing peak demand. He argued that these standing charges, rather than being based on the value or size of a property as was then common, should be based on an individual consumer's maximum demand (and therefore the corresponding increased cost in generation capacity to meet it).[28] Again, Schiller's colleagues found issue with his arguments. W. Fennell of the Mid-Cheshire Electricity Supply Company and the Mersey Power Company[29] declared that "The electricity supply industry appears to be one of the few that has attempted to relate the price charged for an article to the exact cost of getting it to each individual consumer, and many of our troubles are perhaps due to our having attempted something that is verging on the impossible."[30] Schiller was arguing that space heating was a pressure on system demand that could not be dealt with via expansion, a message that many in the industry were not interested in hearing.

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[27] Schiller, "The Control of the Domestic Load," 28.

[28] Paul Schiller, "Towards the 'Correct' Domestic Multi-Part Tariff," *Journal of the Institution of Electrical Engineers—Part I: General* 90, no. 32 (August 1943): 323–36.

[29] At least these were Fennell's affiliations in 1946: W. Fennell, "Fundamental Legislation for Electricity Supply to Consumers," *Journal of the Institution of Electrical Engineers—Part I: General* 93, no. 67 (July 1, 1946): 300.

[30] "Discussions on 'Towards the "correct" Domestic Multi-Part Tariff' by P. Schiller, and on 'General Factors Affecting the Unification of Electricity Supply Tariffs' by C.T. Melling," *Journal of the Institution of Electrical Engineers—Part I: General* 90, no. 32 (August 1943): 338.

As a result of laid down gauntlets by his critics, Schiller became more interested in isolating different components of electrical load, specifically that of space heating. However, isolating the space heating component required untangling the mess that was the total system load. To do this Schiller used the weather, knowing that daylight illumination and temperature would have independent effects on the lighting load and space-heating load respectively. In a paper read before the Institution of Electrical Engineers in March 1944, Schiller compared the load data of Northmet Power Company with the Meteorological Office's *Daily Weather Report* and daylight illumination readings from the National Physical Laboratory for the year ending June 1939 in an attempt to separate the temperature and illumination components from the base load.[31] However, Schiller expressed dissatisfaction with the daylight illumination data from the National Physical Laboratory, saying that it was not self-comparable due to its referring to "variable quadrants of the sky"—clearly on a winters day it would matter whether the photometric sensor was facing North or South due to the position of The Sun.[32] Overall, supply authorities reacted poorly to Schiller's 1944 paper, with many claiming that he had overreached in his conclusion that space heating had an appreciable impact on efficiency. One of these authorities, J. Henderson, claimed that Schiller's method was "clumsy" and "too difficult to apply," and that some of Schiller's results "must inevitably be guesses."[33] The purpose of Schiller's initial weather-based analysis was not to create a system to forecast load, but to show to a sceptical industry that incremental costing was possible and desirable—a point that in-turn was made due to Schiller's concern (later shown to be correct) that the electricity industry's

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[31] Paul Schiller, "An Analysis of the Load on a Modern Electricity-Supply System," *Journal of the Institution of Electrical Engineers—Part II: Power Engineering* 91, no. 23 (October 1944): 433–45.
[32] Schiller, 437.
[33] "Discussion on 'An Analysis of the Load on a Modern Electricity-Supply System' before the Scottish Centre, at Glasgow, 14th November, 1944," *Journal of the Institution of Electrical Engineers—Part II: Power Engineering* 92, no. 28 (August 1945): 268.

mantra of expanding at all costs was unsustainable under the pressures of wartime shortage and demand for space heating.[34]

Clearly Schiller's critics had not been assuaged. As a result, Schiller reached for more advanced mathematical techniques and more reliable observations in an attempt to put his arguments beyond reproach. A 1945 paper by Schiller represents the first change made on the Philadelphia Electric Company's methodology by the UK electricity industry, showing that the relationship between daylight illumination, measured in foot-candles, and load increase was well fitted to a logarithmic curve via regression.[35] This formalised the relationship shown by Dryar (Fig. 6) that was essentially open to the interpretation due to its qualitative categorisation of cloud cover. In addition, Schiller provided the first relationships for load-temperature and load-wind derived from regression techniques (see appendix A). In the opening of the 1945 report, Schiller explicitly outlined his motivations in engaging in the field of load analysis: "(a) for the intelligent planning of extensions or new systems, (b) for tariff purposes and stimulating economic growth more generally, and (c) for the safe and economic operation of power stations by enabling running forecasts of the system demand to be made."[36] Although in recognition of Dryar he acknowledged forecasting as one of the uses of load analysis, his main motivations remained concerns about the overall direction of the industry. Schiller's main interest was not the interaction between the system and daylight, but the nature of the system without this interaction: "Once a satisfactory law is established, the corresponding component of the total system load can be isolated, thus facilitating the analysis of the remaining seasonal load."[37] Schiller

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[34] Schiller remained an obstinate and increasingly vocal battle-axe over this issue for at least the next fifteen years, much to the annoyance of industry leaders: Paul Schiller, "Load Factor Improvement by Seasonal Variation of Charges," April 1959, ESI collection box 434, Science and Industry Museum; Hannah, *Engineers, Managers and Politicians*, 86–88.

[35] Paul Schiller, "Relation Between Daylight Illumination and System Load," Technical Report (15 Savoy Street, London: The British Electical and Allied Industries Research Association, 1945), The IET Library.

[36] Schiller, 3.

[37] Schiller, 3.

wanted to eliminate the lighting load from the analysis of what he was really interested in—the space heating load. He was using the atmosphere as a delicate diagnostic tool, trying to demonstrate to his detractors that the system demand was heading in a worrying direction.

The *Daily Weather Report*, which only recorded qualitative cloud data, was insufficient for Schiller’s needs. In addition, as has already been said, measurements of daylight illumination being taken at the time by the National Physical Laboratory were not considered self-comparable by Schiller. In order to rectify these deficiencies, Schiller himself undertook measurements using self-constructed photometric apparatus (Fig. 7), developed from the arrangement used by the National Physical Laboratory. These instruments were specifically designed by Schiller both to provide a basis of comparison between different days and to record at lower illuminations where the sensitivity of the load was highest. With this in mind, he faced the instruments north to avoid direct sunlight and limited the scale of measurement to 0–100 foot-candles (the daily maximum was 700 foot-candles).

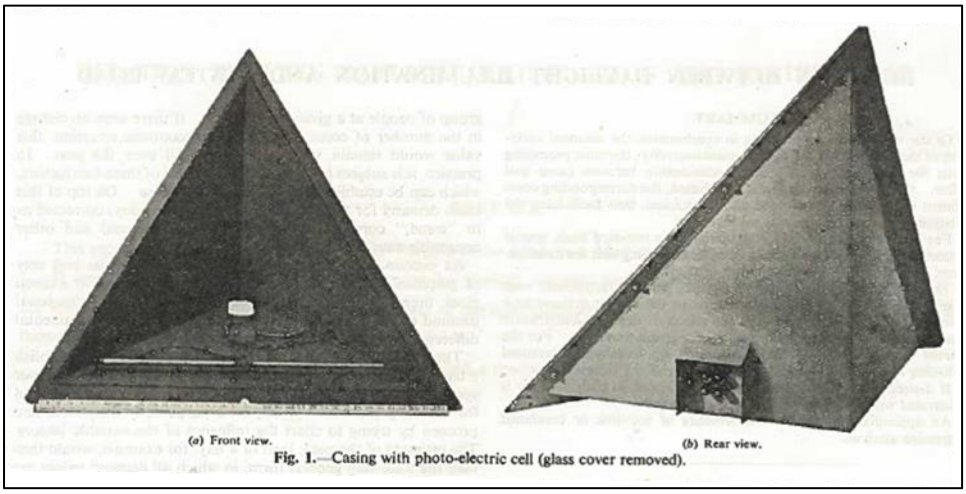

Figure 7. Photometric apparatus constructed by Schiller to measure daylight illumination.[38]

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[38] Schiller, 4.

Schiller acquired load data from the Borough of St Pancras undertaking for the Autumn of 1944, setting up his photometric apparatus on the undertaking's Arlington Road substation. For temperature and wind data he took the readings made at the Meteorological Office's Kew Observatory. Schiller compared the daily 1700–1730h load and illumination against the 1600h temperature (Fig. 8). The earlier temperature reading was due to the delay between the shift of outdoors and indoors temperature, a delay that was intuitively approximated by Schiller.

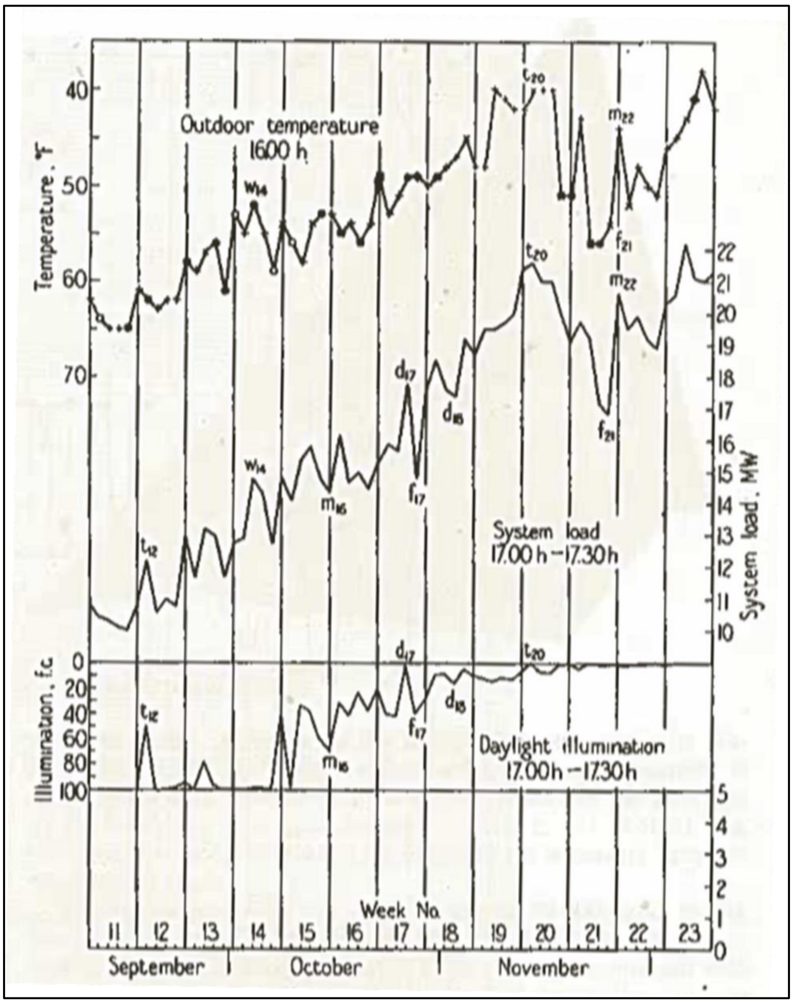

Figure 8. System load compared with outdoor temperature and daylight illumination as plotted by Schiller.[39]

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[39] Schiller, 6.

Schiller made every effort to make his research beyond the reproach of his critics, incorporating formalised multiple regression to prove his weather-load relationships with known errors, a relatively new innovation at the time. Indeed, the majority of the 1945 report in fact consisted of a mathematical appendix provided by Norman Johnson, a young statistician from the Department of Statistics at University College, London, going into detail regarding the mathematical underpinnings of regression analysis.[40] It feels like Schiller was pursuing mathematical "shock and awe" tactics: "The theoretical background of regression analysis is, of course, rather involved, but the information given here and in the Appendix will suffice to enable the method to be practiced without reference to the theory behind it. The basic calculations may even be copied from section 9 of the Appendix without referring to the general exposition."[41] This was a direct rebuttal to Schiller's critics. There was little chance that supply authorities could brand Schiller's new method as "clumsy and difficult to apply" when the application required the copying of an equation, and subjective judgement of the method required a depth of mathematical expertise that was beyond most power engineers at the time.

Schiller's 1945 report pioneered the regression techniques that would later be used across the electricity industry for the incorporation of weather into operational procedure. A representative bibliography published in an Institute of Electrical and Electronics Engineers journal in 1977 recognised Schiller's 1945 paper as an important contribution.[42] Upon nationalisation in 1948, Schiller's research group was taken over by the electricity board's commercial department, where they were prevented from publishing their results due to their resonance with external critics who argued for better costings within the industry.[43] In

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[40] Campbell B. Read, "A Conversation with Norman L. Johnson," *Statistical Science* 19, no. 3 (August 2004): 544–60.

[41] Schiller, "Relation Between Daylight Illumination and System Load," 9.

[42] M.S. Sachdev, R. Billinton, and C.A. Peterson, "Representative Bibliography on Load Forecasting," *IEEE Transactions on Power Apparatus and Systems* 96, no. 2 (March 1977): 697–700.

[43] E.g. Ian Malcolm David Little, *The Price of Fuel* (Clarendon Press, 1953).

addition, the group was ostracised by much of the industry, being starved of data, funds, and talent. As a result of these frustrations, Schiller ended up leaking information to the press, reinforcing the arguments of external critics. Schiller had a combative interpersonal style that further alienated industry leaders from his viewpoints.[44] It would take a series of systematic failures to improve Schiller's position, by which time his warnings were too late.[45] This section has shown how even before the main effects of the capacity crises had been felt, the anticipation of the crises led Paul Schiller to pay closer attention to the weather in order to analyse the electricity supply system. However, his arguments for restraint and efficiency largely fell on deaf ears within the supply system itself, and a known methodology for weather adjustment was only partially exploited by the electricity board.

Consolidation of Weather Adjustment Techniques within the Nationalised Electricity Boards

As the 1940s drew to a close, there was a wider recognition of the challenges facing the UK power industry and the need for greater efficiency, which in turn drove a greater interest in the use of weather information in order to increase efficiency. This interest was partially driven by a series of failures that highlighted serious shortages of coal, such as during the bitterly cold winter of 1946–47. As a result of this "fuel crisis," the Federation of British Industries and the Trades Union Congress made a joint approach to the Minister of Fuel and Power, and in July 1951 the Committee on National Policy for the Use of Fuel and Power Resources was appointed, chaired by the Viscount Ridley.[46] Ridley's report was a

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[44] This personal style can be seen in: Schiller, "Load Factor Improvement by Seasonal Variation of Charges"; Chick, *Electricity and Energy Policy in Britain, France and the United States Since 1945*, 75.

[45] Hannah, *Engineers, Managers and Politicians*, 86–87. It should be noted that Schiller was in contact with Hannah and proofread this text. Hannah's account may reflect some of Schiller's own biases.

[46] *Fuel and Power Resources*, vol. 505, HC Deb (Hansard, 1952), c1749.

vindication for those such as Schiller advocating greater efficiency within the electricity industry. For example, the report specifically bemoaned the unrestricted increase in electric heating demand, suggesting that electric heating was costing the UK 14 million tonnes of coal a year for a job that would cost only 7 million tonnes of coal had the fuel been burned directly or converted into gas or coke. If this heating load was converted to other fuels, the report suggests, load shedding would cease.[47] Ridley's report argued for a new ethos of fuel efficiency within industry—a tone that resonated well with the expansion and refinement of coal-saving weather adjusting techniques.

Within the electricity board, weather adjusting techniques mainly based on the work of Dryar were expanded to all grid control areas in 1949, five years after being introduced in the St Paul's grid control area.[48] This coincided with the setting up of a meteorological unit within the electricity board that aimed "to assist in interpreting forecasts received from the Central Forecasting Office [of the Meteorological Office] and to investigate the special meteorological problems affecting the demand for electricity."[49] The first detailed explanation of the use of weather information by the electricity board is provided in an October 1958 paper published in the proceedings of the Institute for Electrical Engineers by Maurice Davies, a statistician working for the electricity board.[50] Davies's system of

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[47] Matthew White Ridley et al., "Report of the Committee on National Policy for the Use of Fuel and Power Resources" (London: House of Commons, September 1952), 121.

[48] Barnett, "Demand Analysis and Forecasting," 1.

[49] Meteorological Office, "Annual Report of the Director of the Meteorological Office Presented by the Meteorological Committee to the Secretary of State for Air for the Year April 1, 1948 to March 31, 1949" (London: Meteorological Office, 1949), 11, Met Office Digital Library and Archive. It should be noted that the specific activities and the institutional affiliation of this meteorological unit are difficult to ascertain. The Met Office annual reports cease mentioning the unit in 1956: Meteorological Office, "Annual Report of the Director of the Meteorological Office Presented by the Meteorological Committee to the Secretary of State for Air for the Year April 1, 1954 to March 31, 1955" (London: Meteorological Office, 1955), 11, Met Office Digital Library and Archive; Meteorological Office, "Annual Report of the Director of the Meteorological Office Presented by the Meteorological Committee to the Secretary of State for Air for the Year April 1, 1955 to March 31, 1956" (London: Meteorological Office, 1956), Met Office Digital Library and Archive.

[50] Maurice Davies, "The Relationship between Weather and Electricity Demand," *Proceedings of the IEE—Part C: Monographs* 106, no. 9 (October 1958): 27–37. This paper was recognised as significant internationally: Sachdev, Billinton, and Peterson, "Representative Bibliography on Load Forecasting." It appears that it was written to commemorate Maurice leaving the electricity board for academia.

converting Meteorological Office weather forecasts into load forecasting variables remained fundamentally unchanged within the electricity industry for at least 35 years. Davies held a degree in mathematics and a PhD in meteorology for research in fluid dynamics from Imperial College London.[51] Throughout his electricity board career, Davies worked on a broad spectrum of mathematical problems regarding electricity distribution and transmission, and, despite his PhD topic, there is little evidence that he had any institutional affiliation with the Meteorological Office.[52] A non-technical illustrative article repeating the ideas of the 1958 paper was published in *Weather* in 1960.[53] Davies's institutional affiliation and pattern of publication indicates that the UK "home" of weather-based load forecasting research was strongly placed within the electricity research community. The institutional lead taken by the electricity board regarding the incorporation of weather forecasts is demonstrated by the fact it was the electricity board, not the Meteorological Office, that sponsored the laying the telephone cables between regional meteorological offices and regional control centres in 1960.[54] By 1974, the

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[51] "Notes About Authors," *Journal of the American Statistical Association* 56, no. 295 (1961): 737–38. Some of these biographical details were provided to the author by Joanne Ratcliffe, an archives & special collections assistant at the University of Surrey, based on a 1987 retirement notice regarding Davies in a university newsletter: Joanne Ratcliffe to Robert Luke Naylor, "M. Davies 1969," September 15, 2021.

[52] Maurice Davies, F. Moran, and J.I. Bird, "Power/Frequency Characteristics of the British Grid System," *Proceedings of the IEE—Part A: Power Engineering* 106, no. 26 (April 1959): 154–62; Maurice Davies and R.G. Paterson, "Phase Unbalance in Low-Voltage Distribution Systems," *Proceedings of the IEE—Part A: Power Engineering* 109, no. 48 (December 1962): 535–41; Maurice Davies, "Probability Studies of Interconnection Capacity," *Proceedings of the Institution of Electrical Engineers* 117, no. 7 (July 1970): 1382–88. By 1970 Davies was working at the University of Surrey's mathematics department and had become a fellow of the Institute of Mathematics and its Applications, demonstrating a strong institutional affiliation with applied mathematics.

[53] Maurice Davies, "Grid System Operation and the Weather," *Weather* 15, no. 1 (1960): 18–24. If Davies did have any affiliations with the meteorological community, he most likely would have displayed them here under his name.

[54] Meteorological Office, "Annual Report on the Meteorological Office Presented by the Director-General to the Secretary of State for Air for the Year January 1 to December 31 1960" (London: Meteorological Office, 1961), 17–18, Met Office Digital Library and Archive. It seems the regional meteorological offices were set up with industry provision in mind: Graham Sutton, "Committee to Review the Organisation of the Meteorological Office Proposed Organisation of London and Scottish Regional Offices," November 11, 1955, AIR 20/11051, National Archives at Kew. The institutional lead of the electricity industry in the electricity/weather interface is also shown by a joint symposium with the Royal Meteorological Society held in 1945, which was chaired by and mostly attended by power engineers: Forrest, "The Effects of Weather on Power System Operation."

electricity board was receiving seven forecasts a weekday from these regional offices, representing a large increase from the one daily forecast received in 1942.[55]

Davies' system of weather adjustment was much more intricate than that proposed by Dryar fourteen years earlier, incorporating the work of a wide range of fields on the causative relationships underpinning the weather factor. The basic methodology was to use regression techniques on historical datasets, following the ethos of Schiller. However, unlike Schiller, the only explicitly stated aim of Davies' work was to inform the operation of the grid through load forecasts, increasing efficiency rather than arguing for a change in direction for the industry. The first step of Davies's method was to weight the weather information received from the Meteorological Office based on the load density around weather stations. Although around twenty weather stations were used to determine these weights in each grid control area, Davies claimed that six weather stations were sufficient for this purpose, meaning that only forty-two were required nationally. The next step was to manipulate relevant weather information into more immediately useful variables that had simpler (preferably linear) relationships with the load. The raw weather variables found to be useful for load forecasting were temperature, windspeed, cloud coverage, visibility, and precipitation. Temperature and windspeed were important for determining the heating demand, whereas the latter three variables were more important for determining lighting demand. Although Davies acknowledged that precipitation could also influence heat loss in houses, he believed the effect to be largely negligible, with the only real secondary effect of the variable being keeping people indoors. These five raw variables were the bases of four derived variables to be used for load forecasting—effective temperature, daylight illumination index, cooling power of the wind, and rate of

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[55] Barnett, "Demand Analysis and Forecasting," 3–4.

precipitation (the specific mathematical techniques used by Davies are outlined in appendix B).

Effective temperature was designed to reflect the fact that indoor temperature, which was more closely correlated to electrical load, did not respond to outdoor temperature immediately due to the thermal capacity of buildings. Because of variations in building design, Davies decided that the thermal lag constant between indoor and outdoor temperature had to be determined using the historical load and weather datasets only. Using this method, Davies was able to extract an optimum thermal lag constant of twenty-two hours. Davies made several suggestions regarding how this method could be improved. For example, he had assumed the same thermal lag constant for both heating and cooling, which had been found not to be the case for some architectural styles. He also suggested that an extra term could be included to incorporate the central heating of houses. However, it seems that, at least by 1992, these suggestions were never acted upon.[56]

Although Schiller had already found a relationship between load and daylight illumination, Davies outlined a method for converting the standard variables found in Meteorological Office forecasts into illumination values. He did this by comparing seven-years' worth of photometry undertaken at Kew 1947–53 with weather information provided by the Meteorological Office.[57] Firstly, using the Meteorological Office values for visibility (the distance a human can see through the unobstructed atmosphere), Davies was able to normalise his load data for infinite visibility. Then, using the results of theoretical physicists with regard to scattering media, Davies was able to construct a model for determining the transmission through multiple layers of cloud. Combining these two values provided by the

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[56] E. A. Wallis, "Operational Planning—Demand and Generation," in *Modern Power Station Practice: System Operation Vol L*, 3rd ed., vol. 12 (Oxford: Pergamon, 1992), 21.

[57] The standard variables can be assumed to be like those issued within The Daily Weather Report: "The Daily Weather Report 1st April to 30th June 1955" (London: Meteorological Office, 1955), Met Office Digital Library and Archive.

Meteorological Office—visibility and cloud cover—Davies was able to make an estimate of daylight illumination. Again, however, Davies knew his method could be improved. For example, there was little data regarding cloud thickness, snow cover, and smoke pollution, all of which he thought may have had a strong effect on illumination.

The cooling power of the wind incorporated field research done by heating and ventilating engineers, which showed that the effect of wind on inside temperature was more to do with draughts and ventilation than direct heat transmission through walls. Using this information and drawing on the work of other fields in identifying cooling power on bodies, Davies was able to identify the form of the equation illustrating the relationship between wind and load, which he was then able to specify through its application to historic data. The techniques and relationships outlined by Davies remained largely unchanged for at least thirty-five years and were recognisable to load forecasters at the national grid in February 2020.[58]

Unlike for Schiller's work, the journal that published Davies's paper did not go on to publish a follow up discussion entry, indicating that Davies's paper was largely uncontroversial, a fact that is also reflected by the paper's longevity. The only notable change to weather processing methodology before privatisation took place sometime between 1974 and 1992, when rate of precipitation was replaced as a derived weather parameter with four-

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[58] Barnett, "Demand Analysis and Forecasting"; Shanti Majithia, "Weather Correction Process of NGC Demand." The author had the opportunity to visit the national grid control centre in February 2020. Davies himself was quite proactive in promoting the value of his work, arguing strongly against spectral methods that minimised the use of weather information: E.D. Farmer and M.J. Potton, "Development of Online Load-Prediction Techniques with Results from Trials in the South-West Region of the CEGB," *Proceedings of the Institution of Electrical Engineers* 115, no. 10 (October 1968): 1549–58; Maurice Davies et al., "Techniques for Load Prediction in the Electricity-Supply Industry and Developments of Online Load-Prediction Techniques with Results from Trials in the Southwest Region of the CEGB," *Proceedings of the Institution of Electrical Engineers* 117, no. 4 (April 1970): 823–24. Indeed, it took a while for these spectral methods to catch on in load forecasting, with the first computer program for their employment, FORCAS, being abandoned after three years of use: Barnett, "Demand Analysis and Forecasting," 2.

hourly average temperature.[59] In 1974, the electricity board's C. V. Barnett repeated Davies's dissatisfaction with rate of precipitation as a variable, saying that although in theory precipitation would increase the rate of heat loss in buildings, in fact the effect only seemed to be to reduce daylight illumination and to keep people indoors, the latter being shown by the fact that only the evening peak seemed to be effected by rate of precipitation when people had more choice as to whether to remain indoors (i.e. outside work hours).[60] This opinion corresponds to an electricity board textbook from 1971, which also suggested that the effect of precipitation was negligible.[61] This unimportance of rainfall runs against the proverbial and literary perception of British rain being the defining feature of social life.[62]

There were few changes with regard to the processing of weather information within the electricity board after 1958, when Davies published his results. This stagnation in weather-based load research may have reflected the fact that after the mid-1960s efficiency was no longer an overriding political issue within the electricity industry.[63] De-industrialisation, economic depression and the ready availability of North Sea gas led to a relative reduction in demand, and by the 70s there was a surplus of generating plant.[64] When there were shortages of electricity after this period, it was due to factors that could easily be portrayed

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[59] Wallis, "Operational Planning—Demand and Generation," 20–21. With regard to more general demand forecasting, autoregressive functions were introduced in the 1980s. However, as of 1992 these functions complemented rather than supplanted simpler regression models.

[60] Barnett, "Demand Analysis and Forecasting," 7.

[61] Central Electricity Generating Board, *Modern Power Station Practice*, 7:292–93.

[62] Tacitus was associating Britain with rain in the first century: Gordon Manley, *Climate and the British Scene*, 1st ed., Collins New Naturalist Library 22 (London: Collins, 1952).

[63] Indeed, there was a push in the early 70s to get rid of weather-based demand forecasting altogether for short-term demand, prompting Davies to defend their use: U. G. Knight, *Power Systems Engineering and Mathematics: International Series of Monographs in Electrical Engineering* (Pergamon Press, 1972), 183; Davies et al., "Techniques for Load Prediction in the Electricity-Supply Industry and Developments of Online Load-Prediction Techniques with Results from Trials in the Southwest Region of the CEGB"; Farmer and Potton, "Development of Online Load-Prediction Techniques with Results from Trials in the South-West Region of the CEGB."

[64] Hannah, *Engineers, Managers and Politicians*, 286; Susan Owens, "Energy, Participation and Planning: The Case of Electricity Generation in Great Britain," in *Geographical Dimensions of Energy*, ed. Frank J. Calzonetti and Barry D. Solomon, The GeoJournal Library (Dordrecht: Springer Netherlands, 1985), 228.

as beyond the electricity industry's control, such as a shortage of coal due to industrial action during the Winter of Discontent of 1978–79. This contrasted with the capacity crisis, which led to criticism of industry leaders both internally and externally.[65] This section has shown how post war material shortage increased the relative importance of the weather in the electricity board. In 1945, weather adjusting techniques were used in only one limited geographical region of the UK. By the 1950s, not only were weather adjusting techniques expanded across the whole country, but electricity board employees invested substantial effort into refining these techniques. However, although these weather adjustment techniques were sufficient for load forecasts for the next week, there was little the electricity board could say regarding the next winter. With the advent of indicative planning, this was soon to change.

The Atmosphere for Planning

Interest in long-term climate information in the electricity board coincided with interest in the long-term planning that it would inform. The industry needed to know what benchmark weather conditions would be in order to have sufficient planning margins. The first mention of the "average cold spell" standard in the electricity board annual report, in July 1960,[66] followed the election of the second Macmillan government in 1959, a government that encouraged the econometric planning of the economy to achieve full employment. Historian Glen O'Hara has written on how Conservative governments wrestled with the UK economy throughout the 1950s, as the inverse relationships between inflation and unemployment, growth and the balance of payments led to a search for solutions to

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[65] Hannah, *Engineers, Managers and Politicians*, chap. 7.

[66] Central Electricity Generating Board, *Report and Accounts for the Year Ended 31st March 1960* (London: H.M. Stationery Office, 1960), 24.

increase productivity by the end of the 1950s.[67] These shifts in priority led to a move towards econometric planning within the electricity industry, in which the average cold spell standard would play a role.[68]

Speaking in November 1963, Cecil Melling,[69] the deputy chairman of the Electricity Council, outlined longer-term forecasting processes for six, seven, and eight years ahead, stating that since five years was required for the design, construction, and commissioning of a generating system, the six-yearly forecast was especially important for informing contractual decisions. According the Melling, the council relied on three independent forecasts for such purposes. Firstly, each of the twelve regional area boards submitted forecasts based on their local knowledge of industrial developments and consumer behaviour, the latter of which was often determined by representative surveys. Secondly, the electricity board created national forecasts based on trends in previous demand data, with the board deciding that the ten-year trend was best for forecasting six, seven, and eight years ahead (this was more realistic before deindustrialisation at a time when electricity demand was more or less continually expanding). Finally, the Electricity Council's Commercial and Development Department made forecasts based on not only trends, but also analysis of different classes of consumer and discussions with government departments regarding likely trajectories.[70]

In 1963, the Average Cold Spell demand was "determined by calculating the yearly peaks [in demand] that would correspond to the range of weather likely to be experienced in a

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[67] Glen O'Hara, "British Economic and Social Planning 1959–1970" (Doctor of Philosophy, London, UK, University College, London University, 2002).

[68] J. M. W. Rhys, "Techniques for Forecasting Electricity Demand," *Journal of the Royal Statistical Society. Series D (The Statistician)* 33, no. 1 (1984): 28.

[69] Formerly chairman of the Eastern Electricity Board: Cecil T. Melling, *Light in the East: First Decade of the Eastern Electricity Board* (Eastern Electricity, 1987). Melling was also one of Schiller's few allies in arguing for greater attention to be paid to cost research: Hannah, *Electricity Before Nationalisation*, 203.

[70] Melling, "Long Term Planning for Electricity Supply," 7. For a more detailed explanation of such methods in 1984: Rhys, "Techniques for Forecasting Electricity Demand."

span of 100 years and selecting the median."[71] This was calculated by using climatological information to construct a "law of errors" pattern that could then be sampled from. However, a 1963 memorandum from the Ministry of Power claimed that the Meteorological Office's climate data before 1940 was largely insufficient for the purposes of the electricity industry, as the industry was specifically interested in the peak hour (5pm on a winter weekday) and a weighted average of weather conditions across the whole country rather than conditions in particular areas. As a result, more weight was placed on weather data from after 1940, and particularly after 1945, when more suitable information became available.[72]

Later in the 1960s, similar methodologies were used in an attempt to predict the likelihood of more extreme atmospheric events. In 1964, J.[73] Stukins, a Senior Assistant Engineer for the economics section at one of the regional electricity boards (the bodies that the national electricity board sold electricity to), was tasked with supplying answers to the following questions: 1. How many cold winters in the next ten years? 2. How many cold spells in the next ten years? 3. How long will the cold spells last? 4. How severe will they be?[74] To answer them, Stukins used public records mostly provided by the Meteorological Office in response to an earlier request by a parliamentary committee,[75] including records of extreme cold spells since 1878 at Kew Observatory and memoranda of cold spells in central England since the 1600s. He also employed the monthly mean temperatures at sea level

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[71] Select Committee on Nationalised Industries, *The Electricity Supply Industry*, vol. 3, Report 236 (London: H.M. Stationery Office, 1963), 299.

[72] Select Committee on Nationalised Industries, 3:299.

[73] First name unknown. It is assumed that Stukins worked for either the North Western Electricity Board or the Merseyside and North Wales Electricity Board due to specific reference to the north western region in the report. It is possible that they worked for the Central Electricity Generating Board or the Electricity Council directly.

[74] Cold winters were defined as "winters with a mean temperature below 37°F for the three months December, January and February." An extreme cold spell was defined as a minimum of seven days where the average daily temperature did not exceed 32.4°F, and could only be broken by two consecutive daily temperatures above this value.

[75] Select Committee on Nationalised Industries, *The Electricity Supply Industry*, 3:340–43.

since 1901. His method was to statistically analyse the weather records and extrapolate them forward, although he did note that the records did not follow a normal distribution pattern and speculated that a return to the colder conditions of 1740–1840 was possible. Stukins made tentative conclusions of "two to three" cold winters in the next ten years, and one extreme cold spell in the next three winters. For Stukins, the motivation for such research was clearly planning: "There is a need in the Industry for some accepted weather standards when planning plant extension programme some 6 years ahead."[76] The need for planning drove the need for climatological data.

The concept of an Average Cold Spell demand remains an important feature in long-term planning within the electricity industry.[77] Yearly Average Cold Spell demand calculation remained little changed by privatisation in 1990. However, the number of simulated winters for its calculation increased from 100 in 1963, to 500 in 1974,[78] to 20,000 in 2019.[79] This section has shown how in the early 1960s changes in electricity supply transformed the climate into an important planning variable within the industry. Indeed, the electricity board ended up playing an active role in research into climatic changes, providing some initial funding for the University of East Anglia's nascent Climatic Research Unit in the early

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[76] J A Stukins, "Report on Future Weather Prospects (Winters Only) for the Next Ten Years" (Central Electricity Generating Board, November 18, 1964), ESI collection box 406, Science and Industry Museum.

[77] National Grid Company Demand and Energy Analysis and Forecasting Group, "Evaluation of Average Cold Spell Weather Demands for 1990/91," Grid System Management (National Grid Company, April 1991); Majithia, "Weather Correction Process of NGC Demand." It should be noted that this interest in long-term planning was not due to the formal introduction of corporate "strategic planning," which only entered the UK electricity industry in the 1970s: John Grieve Smith, ed., *Strategic Planning in Nationalised Industries* (London: The Macmillan Press Ltd, 1984).

[78] Barnett, "Demand Analysis and Forecasting," 10. In addition, the electricity board made use of the informally defined weekly ACS demand. Weekly ACS demand was the estimated demand for the week of maximum risk of reaching yearly ACS demand. Simulations undertaken in 1974 showed that the 50% risk of reaching yearly ACS demand corresponded to a 12% risk of reaching yearly ACS demand during the week of maximum risk, which focused planning for the winter.

[79] Andrew Richards and Kein-Arn Ong, "Average Cold Spell (ACS) Methodology," Summary Briefing Note (National Grid Electricity Systems Operator, October 7, 2019). For the 2019 ACS calculation, sample weather data was taken from the past 30 years, a period recommended by the World Meteorological Organisation as "the period that is long enough not to be affected by interannual variation, but short enough to be able to ignore climate trends."

70s.[80] This chapter argues that the rise of indicative planning played an important role in the incorporation of climate information into the electricity industry. However, it would be remiss not to consider the possible impact of the harsh winter of 1962–3, the coldest in 200 years.

The Role of Climate Events

It is often assumed that organisations pay more attention to the atmosphere as a result of climate events that have catastrophic impacts. Meteorologist David Spiegler argues that losses occurring from a series of hurricanes in the mid-1950s prompted the foundation of the Travelers Weather Research Center, the world's first privately-owned meteorological research institute.[81] Historian of science Vladimir Janković has argued that major climate anomalies of the early 1970s, amongst other factors, contributed to the rise of industrial and applied meteorology.[82] Geographers David and Stanley A. Changnon state that "The severe drought of 1988 followed by a series of major catastrophic storms in the 1990s caused major regional and national losses, creating awareness of the need to better consider the impacts of climate conditions on business and industry."[83] My thesis, in particular the current chapter, complicates this viewpoint, arguing that attention was paid to the atmosphere by the UK utilities industries for reasons that were more endogenous to the industries themselves. To further demonstrate this point, I examine the winters of

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[80] Allan Piper, "Lamb's Unit to the Slaughter?," *Nature* 248, no. 5448 (April 1, 1974): 466–67. A similar argument that economic planning led to interest in climate, this time within the Shell corporation with regard to UEA, can be found in: Elliot Honeybun-Arnolda and Martin Mahoney, "The Temperature of the Archives: The Climatic Research Unit, UEA, 1971–1986" (Temperatures and Temporalities, Cambridge, 2022), 4.

[81] David B. Spiegler, "A History of Private Sector Meteorology," in *Historical Essays on Meteorology 1919–1995: The Diamond Anniversary History Volume of the American Meteorological Society*, ed. James Rodger Fleming (Boston, MA: American Meteorological Society, 1996), 417–41; "The Travelers Weather Research Center," *Weatherwise* 7, no. 6 (December 1, 1954): 159.

[82] Janković, "Working with Weather."

[83] Changnon and Changnon, "Major Growth in Some Business-Related Uses of Climate Information."

1946–7 and 1962–3, and show how these landmark events made little direct impact on how weather and climate was conceptualised within the electricity industry.

The pressure on the electricity supply system in the 1940s has already been discussed in this chapter, but it is important to provide further context for the supply situation in the early 1960s. Any relaxation of pressure on the electricity board's generating capacity due to industrial decline was not to come until the mid-1960s. The early 1960s presented new challenges that had not been predicted by planners within the electricity boards, and not accommodated by the electricity board's generating plant construction program. Demand for electric space heating, previously somewhat stymied by public outreach and the promotion of off-peak storage heaters,[84] suddenly shot up as the 1956 Clean Air Act came into force. The burning of coal in "Clean Air Zones" was outlawed, and families reached for electric space heating as a clean alternative sometimes under government subsidy. This caused renewed pressures for the electricity industry. In 1962, the cities of Sheffield and Huddersfield reported a yearly domestic demand increase of 27% and 25% respectively.[85] These values did not take into account the effects of the 1962–3 winter, which was the coldest in two centuries. For the first time in more than a decade, the grid system could not have supplied the UK's demand even if it were to run perfectly with no breakdowns, representing a second capacity crisis for the industry.[86]

The winters of 1946–7 and 1962–3 have become landmark events in the history of the UK. The harsh winter conditions of 1947 were exceptional for how long they lasted without reprieve. From late January to early March, Easterly winds drove a succession of snowstorms across the country. According to the UK Meteorological Office, snow fell every

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[84] Carlsson-Hyslop and Pearson, "How Did the Electrical Development Association Attempt to Mould Domestic Electricity Demand in Britain, 1945–1964?"
[85] D. F. Hunt to P. A. Lingard, "Effect of Smoke Control on Domestic Load Development," February 5, 1963, ESI collection box 425, Science and Industry Museum. In this way, changing perceptions of the atmosphere led to changes in electrical load through legislation.
[86] Hannah, *Engineers, Managers and Politicians*, 290–91.

day for 55 successive days, and cold temperatures ensured that much of this snow settled, blocking off roads and railways.[87] As a result of destroyed crops, bread and potato rationing was introduced for the first time, measures unprecedented even during wartime.[88] A population that had been promised deliverance from wartime austerity suddenly found many aspects of their lives becoming harder, contributing strongly to the ruling Labour government nearly losing the 1950 general election.[89] Similarly, the winter of 1962–3 was the coldest in 200 years. Wintery conditions were brought to the UK by a high-pressure system in late December 1962, bringing blizzards and snowdrifts up to six meters deep. Animals died as farmers could not reach them through the snowdrifts. Unlike in 1947, the snow was not continuous, but the weak winter sun did little to warm the country up, and the open skies led temperatures to plunge as low as -22°C. Even as temperatures finally rose, the misery was not over, as the thaw led to widespread flooding during both winters.[90] For a country that usually only experiences sporadic sprinkles of snow and only a handful of days below freezing during the average winter, these events were truly outstanding.

The legacy of these winters remains strong within the UK cultural and media landscape. Important anniversaries are marked, and comparisons are made whenever a cold winter arrives. Several books have been written about the events, embedding them into wider cultural and political contexts.[91] Media narratives have had a strong influence over how the

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[87] Meteorological Office, "Severe Winters," Met Office Website, April 20, 2015, accessed September 14, 2022, https://www.metoffice.gov.uk/weather/learn-about/weather/case-studies/severe-winters.

[88] Anthony Sutcliffe, *An Economic and Social History of Western Europe since 1945* (Routledge, 2014), 31.

[89] Frederic A. Youngs Jr et al., *The English Heritage: Since 1689 v. 2: Volume II: Since 1689*, 3rd edition (Wheeling, Ill: Wiley-Blackwell, 1999), 425.

[90] Meteorological Office, "Severe Winters."

[91] Ian McCaskill and Paul Hudson, *Frozen in Time: The Worst Winters in History*, 1st Edition (Ilkley: Great Northern Books Ltd, 2006); Juliet Nicolson, *Frostquake: The Frozen Winter of 1962 and How Britain Emerged a Different Country*, First Edition (London: Chatto & Windus, 2021); Alex J. Robertson, *The Bleak Midwinter, 1947* (Manchester University Press, 1987).

winters have been perceived ever since the events themselves. Indeed, historian of meteorology Alex Hall and environmental historian Georgina Endfield have shown how media narratives at the time of the winters have sculpted individual recollections of the event, even in some cases when media narratives conflicted with real lived experience.[92] Another societal factor that shaped perceptions of these winters was failures of electricity and gas infrastructure, which is evidenced by quotes from first hand witnesses as well as then-contemporary news articles.

A *Manchester Evening News* article from the 29th of January 1947 detailed how electric power throughout the city had been cut off between 7:55 and 9:30 am, so "people who relied on electricity shivered over cold breakfasts."[93] Those who instead relied on gas were not much better off, as the gas supply could only be provided at a quarter of normal pressure—it would take half an hour to boil a cup of tea. People turned to more basic forms of heating and cooking, often plundering local woodlands for firewood. Shortages of power also had a devastating impact on employment, as industry had to be shut down due to lack of power, meaning knock-on effects for other parts of the economy as consumer spending slowed.[94] One student described the depressive atmosphere to a mass survey[95]:

> What the crisis means to me is: 1.30–3.30: lie without lights; my bedroom is rather dark so this means I cannot read. I cannot listen to the radio. I cannot sit up in bed and do anything since the power is off and I cannot use my electric fire. The place is almost unlivable in from the point of view of heating, from early morning to six at night. I hate cold. I wish I were back in Egypt. I wish I

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[92] Alexander Hall and Georgina Endfield, "'Snow Scenes': Exploring the Role of Memory and Place in Commemorating Extreme Winters," *Weather, Climate, and Society* 8, no. 1 (January 1, 2016): 5–19.
[93] Robertson, *The Bleak Midwinter, 1947*, 107.
[94] Robertson, *The Bleak Midwinter, 1947*.
[95] Robertson, 113.

> were anywhere but in this goddammed country where there is nothing but queues and restrictions and forms and shortages and no food and cold.

The failure of the utilities systems meant the winter was felt more strongly by the population. Undoubtedly some of the most affected were housewives, who were forced to run a household without even the most basic amenities of modern life. They were not helped by central government decision-making, which prioritised industry by enforcing restrictions on domestic energy consumption during daylight hours outside of lunch. One mass observation respondent described the difficulties in her "all-electric house with one decorative but extremely inefficient coal fire. I have found it extremely difficult to deal with the baby's daily washing. Everything else, cooking, ironing, washing, cleaning, bathing, has either to be arranged for other times or improvised—hay box for cooking, tin kettle in fire for small quantities of hot water, flask kept for hot drinks etc."[96] The lot of housewives was not much improved during the 1963 winter, as recounted by author Juliet Nicholson: "Mothers were given piles of the latest 'disposable' nappies to take home as the flannelette version would no longer dry on freezing washing lines. Meanwhile the Central Electricity Generating Board [for this chapter known as 'the electricity board'] suggested helpfully that housewives might postpone their ironing."[97] Many of the personal stories of hardship during the winters would not have been possible had sufficient electricity supplies been maintained. System failures sculpt perceptions of meteorological events. These failures forced people to feel the cold and the dark, highlighting societal inequalities in the process.

If climate events had a central impact on the operational use of weather and climate information, the winters of 1947–8 and 1962–3 would have been just such climate events.

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[96] Robertson, 112.

[97] Nicolson, *Frostquake*.

However, these events and others do not appear to have had a strong effect on how the utilities industries conceptualised the atmosphere, although they did have notable effects in parliament and the media. The winter of 1947–8 acted as little more than a magnifying glass for the shortages of coal that plagued the immediate post-war UK economy.[98] Indeed the Ridley report, a prime driver of efficiency within the electricity industry, described the events of 1947 as a "coal crisis" rather than a harsh winter.[99] These coal shortages and the resultant power cuts, rather than the harshness of a particular winter, drove efforts to improve efficiency that resonated with weather optimisation.[100]

However, it seems that the winter of 1962–3 focused minds on climatological aspects of demand within parliament. As the winter raged, the parliamentary Select Committee on Nationalised Industries[101] requested that the Ministry of Power examine the possibility that the industry had emerged during an era of unusually mild winters and whether this might have allowed an insufficient margin of spare generating capacity in planning. In response, the ministry consulted the electricity board as well as long-term climatic records from the Meteorological Office, providing a memorandum in March 1963. The reply highlighted that the industry used a planning variable known as the average cold spell, and that this variable was calculated using climatic data that was weighted towards the post-war years due to the availability of sufficient data. Although the memorandum agreed that the 40 winters after 1900 were mild, it also claimed that the winters since 1945 were comparatively more severe, and therefore that planning had largely not been affected by the relatively mild start of the century.[102] It seems that factors that were endogenous to the economy, rather

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[98] Alexander Hall, "Risk, Blame, and Expertise: The Meteorological Office and Extreme Weather in Post-War Britain" (Doctor of Philosophy, Manchester, UK, University of Manchester, 2012).

[99] Ridley et al., "Report of the Committee on National Policy for the Use of Fuel and Power Resources," 5.

[100] *Fuel and Power Resources*.

[101] For the origins of the committee: Ernest Davies, "The Select Committee on Nationalised Industries," *The Political Quarterly* 29, no. 4 (1958): 378–88.

[102] Select Committee on Nationalised Industries, *The Electricity Supply Industry*, 3:299.

than the harshness of weather events, drove an interest in atmospheric information within industry.

"Gradual Computerisation"

The introduction electronic computer is often seen as one of the most important developments within mainstream atmospheric science.[103] This section considers whether electronic computers were similarly important for the incorporation of atmospheric information into the electricity industry. The turn of the 1960s heralded the first electronic computers both in the Meteorological Office and in the electricity board.[104] However, it appears that the electricity board was not quick to use this technology for load forecasting purposes, especially with regard to weather information. It is at the end of the 1960s that we see one of the few ministerial interventions concerning weather-based load forecasting based on numerical data processing by new computing infrastructures. A December 1968 internal report within the Ministry of Power indicated interest in the development of a joint system between the gas and electricity industries for the reception and processing of Meteorological Office weather data.[105] This was as part of wider efforts to increase co-operation and standardisation within the ministry's industries with regard to computers, partially resulting from parliamentary pressure to use British computers within the

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[103] Edwards, *A Vast Machine*, chap. 6; Harper, *Weather by the Numbers*.

[104] Brian Golding, Kenneth Mylne, and Peter Clark, "The History and Future of Numerical Weather Prediction in the Met Office," *Weather* 59, no. 11 (2004): 299–306; Electricity Council Financial Department, "Present and Proposed Area Board Computer Installations" (Electricity Council, December 1968), ESI collection box 383, Science and Industry Museum. Politicians repeatedly tried to interfere with the procurement of computers, arguing that it was essential that public bodies preferred British computers over foreign competition: W. E. Fitzsimmons to B. C. O Murphy, March 13, 1969, ESI collection box 383, Science and Industry Museum. Indeed this political pressure was almost certainly in the service of International Computers Limited, pet project of Minister of Technology Tony Benn: John Lee, "Britain to Finance Computer Merger: Britain Will Aid Computer Linkup," *New York Times*, June 12, 1968, sec. Business and Finance. For more on the history of the British computer industry: Hendry, *Innovating for Failure*.

[105] Brooks, "Co-Operation between the Nationalised Industries in the Selection, Purchase and Use of Computers" (Ministry of Power, December 30, 1968), ESI collection box 383, Science and Industry Museum.

nationalised industries. In March 1969, W. E. Fitzsimmons, an assistant secretary within the Ministry of Power, relayed the report's concerns to the Electricity Council, indicating that they were in the interest of the parliamentary under-secretary of state at the ministry, Reginald Freeson.[106] In turn, the Electricity Council passed the letter on to electricity board staff, where the ministerial suggestion of a joint weather-processing system was not met with enthusiasm. This was, as one board employee claimed, due to fundamental differences in gas and electricity, with gas being storable within the distribution system.[107] For electricity board employees, the differences between gas and electricity were too great for common use of weather information.

In May 1974, a conference on load forecasting was held in Horsely Towers, Leatherhead. Although most contributions concerned long-term economic forecasting, a paper contributed by Colin Barnett outlined the "gradual computerisation" of the weather information processing in the electricity board's National Control.[108] Before computers were used specifically for load forecasting, a series of programs were developed for the analysis of historic weather data, with work beginning in 1965. From 1971, daily load shapes and derived weather variables were being digitally archived on magnetic tape in a format that was easily retrievable by other electricity board programs.[109] These programs included REGAL, which undertook the regression analysis as per Davies in order to allow load forecasting, and WELAV, a weather-demand-generation simulation program. The first program for processing weather forecasts from the Meteorological Office in order to produce load forecasts, known as FORCE (FORecasting for Control Engineers), was introduced in the electricity board's National Control in August 1973, eight years after work

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[106] Fitzsimmons to Murphy, March 13, 1969.

[107] B. H. P Johnson to L. H. Thompson, "Computers—Co-Operation between Nationalised Industries," April 9, 1969, 2, ESI collection box 383, Science and Industry Museum.

[108] Barnett, "Demand Analysis and Forecasting." Barnett also laid out in detail the extent of weather data sent to the electricity board from regional offices of the Meteorological Office, which had increased markedly since the 40s.

[109] Barnett, 14; Wallis, "Operational Planning—Demand and Generation," 20.

on the issue started and twelve years after the first electricity board computers. The system of programs set out by Barnett for converting weather variables into useful load forecasting variables continued in use until at least 1981 (albeit on different hardware),[110] and remained little-changed by the time of privatisation. By 1992, the Meteorological Office and electricity board computers were interfaced by telex, with forecasts being automatically compiled in the electricity board's databank.[111] The gradual introduction of digital computers within the electricity board had little effect on the fundamentals of weather processing. The basic methodology of linear regression outlined by Davies remained the same.[112]

Creating the Electric Atmosphere

During the first two post-war decades, when generating plant was often insufficient for the needs of the nation, individuals within the UK electricity industry engaged with, manipulated, and created weather information to suit their needs. Whereas later power shortages such as that during the Winter of Discontent 1978–79 could be construed as due to factors outside the electricity industry's control,[113] the capacity crises were a systematic failure partially driven by a dogmatic drive towards an electric future. Technical and scientific advisors used climate information to uncover these systematic failings before they led to problems, aiming to use the atmosphere to analyse the system. Shiller, for example, looked at how the load changed without the influence of daylight illumination. However, rather than stripping the system of a meteorological component, Schiller assisted

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[110] The Monopolies and Mergers Commission, "Central Electricity Generating Board" (London: UK House of Commons, May 1981), 334.

[111] Wallis, "Operational Planning—Demand and Generation."

[112] In conversation with the author, Samuel Randalls has suggested that the recent difficulty in integrating hydrodynamical simulations into large technological systems may have partly resulted from the fact that the methodology for processing atmospheric information within such systems predates the use of digital computers.

[113] Indeed, the 1970s represent a time of overcapacity in the electricity industry: Hannah, *Engineers, Managers and Politicians*, 286–87.

in incorporating the weather into the system. His wartime work regarding the effect of daylight illumination on system load represented one of the earliest analyses that would underpin the future processing of weather data by the electricity industry.

By the 1950s, the electricity boards were systematically processing weather data, both historic and forecasts, to assist in operational procedure of the electricity grid. Employees of the electricity board synthesised meteorological records with the electricity industry's archive of electricity demand in order to forge new variables that could lubricate the demand forecasting process. By the early 1970s, the electricity board was creating a meteorological archive of its own on magnetic tape within National Control. This active archive consisted of pre-processed weather values and their usage by a number of electricity board programs used for further processing, simulation or forecasting, representing an early example a dynamic meteorological archive.[114] The electricity board's meteorological archive was essential to the operation of the electricity grid, being used for planning on all scales, from minute-by-minute load dispatching through load forecasts, to year-by-year plant construction through the calculation of Average Cold Spell demand.

This chapter has brought to light a systematic body of weather knowledge that was motivated and mostly formed outside of the meteorological community.[115] In the case of electricity, understanding when, how, and why weather information came to be

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[114] Vladimir Janković, "Montage and Metamorphosis: Climatological Data Archiving and the US National Climate Program," *Science in the Archives: Pasts, Presents, Futures*, 2017, 223–46.

[115] This chapter focuses on the use of weather as a useful tool for forecasting electricity demand, but individuals within the electricity industry also investigated weather as a direct risk to infrastructure. In early 1934 Central Electricity Board engineer John Forrest established a small laboratory (with a staff of no more than five) in Croydon to investigate the behaviour of 132kv insulators under various weather conditions. This small laboratory developed into the Central Electricity Research Laboratories at Leatherhead, Surrey, which Forrest led until 1973. In 1942, Forrest joined the Royal Meteorological Society, becoming one of the founding editors of the society's journal *Weather*. Forrest's contributions to meteorology were not just institutional – he also made research contributions regarding the detection of thunderstorms via radiosonde: Thomas Edward Allibone, "John Samuel Forrest, 20 August 1907–11 November 1992," *Biographical Memoirs of Fellows of the Royal Society* 40 (November 1, 1994): 105–26; Robert Luke Naylor, "John Samuel Forrest: The Power Engineer Who Helped Found Weather," *Royal Meteorological Society History Group Newsletter* 2021, no. 1 (2021): 4–7.

incorporated into operational procedure requires an in-depth understanding of the technical and political challenges facing the UK industry. These challenges were such that, even when ideal weather information was not available from the meteorological community, engineers and mathematicians within the industry were motivated and able to construct models and apparatus to circumvent these deficiencies. In addition, the emergence of new technologies such as the wider utilisation of regression analysis and digital computers cannot be seen as the prime drivers for the use of atmospheric information in the operation of the electricity grid. These became important tools for load forecasters as they emerged, but the operational use of weather information within electricity predated the use of regression and computers and was driven by a political and economic need to increase efficiency in a period of shortage for UK industry. If weather historians are to understand how weather information came to affect the majority of people during ordinary times in their lives—whether through their lights, their fridges, or their incubators—it is essential to look beyond meteorological institutions and examine technological systems.

Chapter Three—Bringing on the Heat: The Atmosphere in the UK Gas Industry

Although the electricity industry underwent considerable expansion in the post war period, the nature of the system remained relatively consistent. In 1948, the electricity distribution system was nationally integrated, centrally controlled, and mainly reliant on the use of coal-fired power stations. Much the same could be said of the electricity distribution system in 1980. In contrast, the gas industry in the UK went through a fundamental transformation between those same years, which had a consequential impact on the industry’s weather sensitivity and consequently the use of atmospheric information. This chapter examines the incorporation of atmospheric information into the operation of the nationalised UK gas industry. It argues that as the gas transmission system became more centralised, optimised, and remotely controlled, atmospheric information became an increasingly exploitable resource that could be used to further reduce redundancy in the system, and that new technologies and expansion made the system more weather-sensitive, not less. The atmosphere transitioned from a subject of sporadic local knowledge and intuition into a set of formal variables that were essential for the daily running of the gas transmission system, for example allowing the British Gas Corporation to provide newly established gas platforms in the North Sea with daily demand forecasts as required by contract. The atmosphere also became an essential feature in planning—in 1984 even a 1% reduction in the standard deviation of the percentage error of daily weather forecasts could reduce the investment in regional gas storage by £50m.[1] Transformations in the gas transmission system transformed both the visibility and value of the atmosphere within the industry.

Gas is a storable commodity, whether through “line packing” in transmission pipes, the use of purpose-built high-pressure cylinder installations, or the exploitation of underground caverns. In fact, because offshore natural gas production cannot be “switched off” completely without huge economic costs, storage forms an essential component of the day-to-day running of the gas transmission grid. Gas that is pumped ashore during the night has to be stored for several hours in order to be used when demand is highest during the day. In addition, a certain portion of storage is kept for security, principally to offset unexpected changes in demand such as those during a particularly cold day. However, these storage methods have very real economic costs for the gas distributor, especially

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[1] Frank Lyness, “Gas Demand Forecasting,” *Journal of the Royal Statistical Society. Series D (The Statistician)* 33, no. 1 (1984): 9–21.

when high pressures need to be maintained, meaning that their use is kept to a minimum.[2] In order to minimise storage, accurate short-term demand forecasting is required to synchronise demand and supply (although the natural gas supply cannot be switched off, it can be attenuated slightly), and in the case of domestic usage weather is a prime determinant of demand.

In contrast, before and immediately following the Second World War, the gas supply system could be considered a patchwork of largely independent supply systems with little transfer of product taking place between competing undertakings. Gas was manufactured through the carbonisation of high-grade “coking coal” in ovens known as retorts, producing the valuable industrial by-products of coke and tar in the process. These by-products incentivised a decentralised industry, as gasworks were located near to manufacturing plants that needed them (e.g. coke for steelworks, tar for industrial chemical manufacturers). However, in the immediate post-war period the price of high-grade coking coal skyrocketed, even more so than the lower-grade coal that the electricity industry could use in its plants. As a result, at nationalisation in 1948, gas was considered hopelessly uncompetitive against electricity. This situation, in addition to general post-war shortage, led to a rapid rationalisation and optimisation of the nationalised industry, as inefficient gasworks were closed the remaining works connected into large regional networks under the control of twelve area boards. Meanwhile, the Gas Council, a body responsible for research and co-ordination within the nationalised industry, sponsored the development of new oil-based manufacturing techniques (Fig. 9). By the mid-1960s, the gas industry was moderately competitive against electricity.[3]

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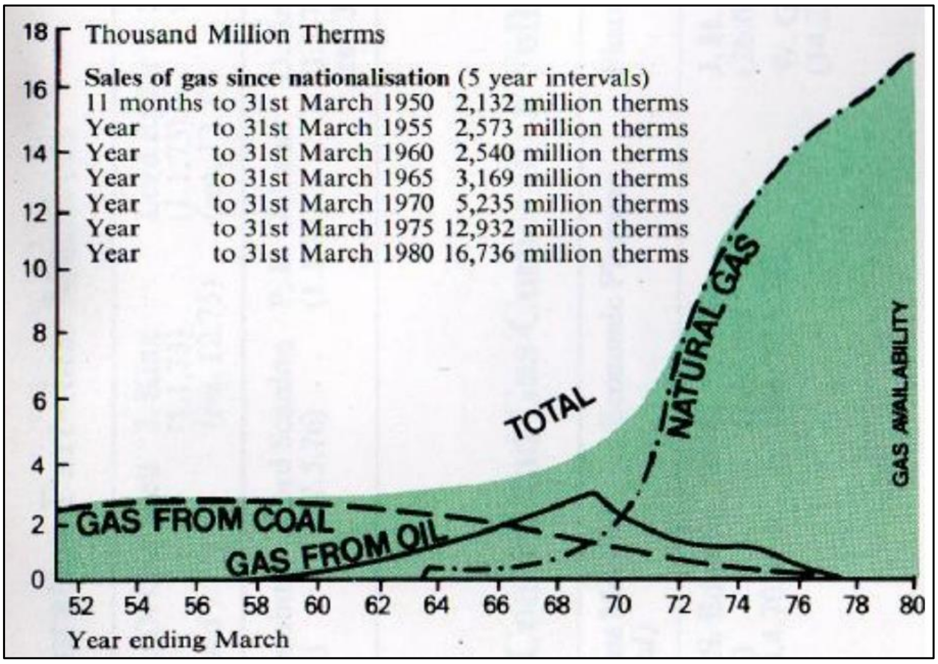
[2] E. N. Tiratsoo, *Natural Gas*, 2nd ed. (Beaconsfield, England: Scientific Press, 1972), chap. 10; British Petroleum, *Gas Making & Natural Gas*, 1st ed. (Britannic House, Moor Lane, London. EC2Y 9BU: BP Trading Limited, 1972), chap. 18.

[3] Trevor Illtyd Williams, *A History of the British Gas Industry* (Oxford University Press, 1981).



Sales of gas since nationalisation (5 year intervals)

11 months	to 31st March 1950	2,132 million therms
Year	to 31st March 1955	2,573 million therms
Year	to 31st March 1960	2,540 million therms
Year	to 31st March 1965	3,169 million therms
Year	to 31st March 1970	5,235 million therms
Year	to 31st March 1975	12,932 million therms
Year	to 31st March 1980	16,736 million therms

Figure 9. Sales of gas by the nationalised industry 1951–80.[4] The therm is a unit of heat energy. Pre-1965 natural gas was imported via ship from North Africa.

However, this moderate improvement of fortune for the industry was overshadowed by the dramatic discovery of natural gas in the North Sea in 1965, requiring both technical and institutional transformation within the industry. From 1965 to 1972, the Gas Council, which had previously mostly undertaken co-ordination and research functions, was transformed into the British Gas Corporation and superseded the area gas boards. The British Gas Corporation was solely responsible for the development and maintenance of UK gas supply until privatisation in 1986. In order to justify its monopolistic position, the Gas Council had to guarantee that it could get the glut of North Sea gas to market as quickly and efficiently as possible. As a result, the Gas Council was central in developing the National Transmission System, which connected the entire gas distribution network into a single system. Even so, exponentially increasing supply became a problem for the Gas Council, leading to an aggressive marketing campaign that successfully increased the use of natural

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[4] British Gas Public Relations Department, “Gas Chronology: The Development of the British Gas Industry” (Rivermill House, 152 Grosvenor Road, London: British Gas, November 1980), 23.

gas in industry during the early 1970s.[5] By necessity, changes to the method of supply led to changes in the methods of distribution. Coal gas had been mostly manufactured at small works across the country, leading to a patchwork of largely independent supply systems. In these systems, the manufacture of gas was dictated by engineers within the individual gasworks, meaning that redundancy, local knowledge, and rules of thumb were used to ensure security of supply in the face of variable weather. In contrast, natural gas extraction is a much more centralised endeavour, with high-pressure gas being pumped ashore via a handful of distribution centres. In this system, numerical and statistical weather information became increasingly essential, as the gas industry lost the ability to synchronise its production with demand, and high-pressure gas storage became increasingly expensive. As a result, as this chapter will show, rapid expansion and technological innovation led to a system that was more sensitive to atmospheric fluctuations.

The Atmosphere and Gas Supply before the Second World War

The earliest incorporation of the weather into gas supply operation relied on the intuition and ad-hoc observations of individual dispatchers. In 1909, the superintendent of the City of Leeds Gas Mains and Distribution Department expressed frustration at the failed attempts to automate gas distribution, admitting that supply had to be at the discretion of the individual dispatcher according to weather conditions. He believed that this was a poor system, as the weather conditions at the dispatching station could differ substantially from some of the areas it was supplying. The superintendent saw fluctuations in demand as a secondary problem with regard to weather response in the transmission system; he was more interested in the changes of gas pressure within the pipe induced by fluctuations in

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[5] Williams, *A History of the British Gas Industry*; Jerome D. Davis, *Blue Gold: The Political Economy of Natural Gas* (Springer Netherlands, 1984).

outside temperature, and hoped for an automatic system to reduce the variations in pressure experienced by the consumer, avoiding either a dangerously high pressure or an insufficiently low pressure of supply.[6] Concerns over safety and security are less central in a 1920 textbook, which sees the drop in temperature between the station meter and the consumer's meter in economic terms. Simply, a drop in temperature decreased the volume of the gas, leading to an unaccounted loss of the product of the order of 1 percent for every 4°F. In order to rectify this, engineers made a back-of-the-napkin calculation as to the average yearly temperature (using unspecified climatological records) at the consumer's meter per unit volume of gas, and just measured outgoing gas at the station meter at a constant temperature all year round and applied the 1 percent for every 4°F. Thus, the unaccountable loss was made somewhat accountable with the use of climatological data.[7]

As the century wore on, the nature of domestic gas consumption changed as gas increasingly began to be used for central heating instead of lighting.[8] As a result, temperature became the dominant aspect of weather affecting an increasingly variable gas demand, leading engineers to pay more attention to the load-temperature relationship. In 1929, Frederic Gorman, the Deputy Engineer of the South Suburban Gas Company, wrote how it "behoves" the distribution engineer to be a "student of the weather" and that considerable help could be found by telephoning the Meteorological Office, which would provide a 24-hour forecast for their particular area "for a very small sum per month." The use of longer-term 24-hour forecasts, as opposed to the hour-by-hour forecasts sought by the electricity industry, was made possible by the use of gas holders, which were able to offset shorter-term fluctuations in demand. As a result, gas undertakings had more lenient

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[6] Walter Hole, *The Distribution of Gas*, 3rd ed. (London: John Allan & Company, 1912), 55–57; R. F. Francis, "Grid Control—Past, Present and Future" (Institution of Gas Engineers, Wales District Section, June 1991), 5.

[7] Henry Woodall and B. R. Parkinson, *Distribution by Steel (Gas and Water) with High-Pressure Tables for Flow of Gas in Mains*, 2nd Edition. (Benn, 1920), 92–93.

[8] E. G. Stewart, *Town Gas: Its Manufacture and Distribution*, 1st ed. (London: H.M. Stationery Office, 1958), 40–42.

requirements in synchronising supply and demand due to storage and other redundancies in the system, as summarised by J. H. Dyde of the Eastern Gas Board: “It is true that the gas engineer of the single small, medium or even large Works of pre-war days worried little about the vagaries of the weather, the day-to-day and month-to-month changes in his demand. There were always a few extra retorts available, another shift of water gas to put on, and his generally adequate holder capacity to cushion the unexpected changes.”[9]

Perhaps as a result of these safeguards, Gorman gives the impression that any precise knowledge of the relationship between temperature and the hourly system load was at that time mainly aspirational.[10] Instead, it seems that disparate rules of thumb were employed that varied from gasworks to gasworks, often depending on the engineer’s intuition regarding the local area. D. G. Rose, a coke manager writing in 1950, expressed admiration for the intuitive art of forecasting demand: “That some of the variations of daily gas output are closely linked with atmospheric temperature and, no doubt, with other attributes of the weather as well, is axiomatic; and that those who have lived close to the problem have an intimate working knowledge of their nature is the reason why gas stocks have been so well regulated for years past without the use of any detailed analysis […]. Experienced valvemen have an uncanny knack of assessing the consumers’ needs from day to day.” It seems that while the engineers of individual works, rather than centralised controllers, were in charge of production, plentiful redundancies, local knowledge, and intuitive rules of thumb were up to the task of ensuring security of supply.

A widely used rule of thumb was that demand varied by one percent with each degree Fahrenheit change in temperature in a one-on-one comparison with consumption the

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[9] D. G. Rose, “A Background to Some Economic Problems in the Gas Industry,” Communication (1, Grosvenor Place, London: Institution of Gas Engineers, January 1950), 41, IGE_1950_352_161, National Gas Archive.

[10] Frederic G. Gorman, “The Incident of the Peak Load” (London: Institution of Gas Engineers, 1929), IGE_1929, National Gas Archive.

previous year.[11] In 1938, a graphical technique known as the degree day method was introduced to the industry from the United States, which extrapolated the "one percent demand per degree Fahrenheit" rule of thumb into a slightly more formal system in order to measure the efficiency of the heating requirements for buildings. A degree day is a scalar quantity that measures the cumulative temperature difference below a baseline (usually 60°F for the UK during this period) over time—a quantity that was found to be proportional to fuel required for heating purposes. For example, a week at a constant 59°F would result in seven degree days, whereas a week at 58°F would result in fourteen. Rather than looking at the absolute consumption of gas to measure heating efficiency, engineers would calculate the gas supply per degree day, usually over a period of months or years. In order to make these calculations, gas engineers made use of climatological data from regional meteorological stations. Usually, the average daily temperature was simply calculated as the mean of the minimum and maximum temperature for the day, although by the mid-1960s hourly temperatures were being used where available. It is clear that from the late 1930s climatological information was being passed from the Meteorological Office to the gas industry in order to (indirectly) help improve efficiency in the gas supply system. However, this service was discontinued during the Second World War, showing that in the early days at least this was not seen of by the UK Government as an essential service.[12] Indeed, it appears that until the late 1950s the Meteorological Office did not provide specialist forecasts for the gas industry; the Meteorological Office annual report from 1947 only makes mention of "warnings of cold spells."[13] Instead, the gas industry had to make do

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[11] Berrisford, "The Relation between Gas Demand and Temperature," June 1, 1965, 231; "Degree Days: Their Use and Application for Checking and Computing Fuel Consumption," Technical Handbook (London: The Gas Council, 1965), 3, 7863, National Gas Archive.

[12] "Degree Days."

[13] Meteorological Office, "Annual Report of the Director of the Meteorological Office Presented by the Meteorological Committee to the Air Council for the Period August, 1945 to March 31, 1947" (London: Meteorological Office, 1947), 12, Met Office Digital Library and Archive. It seems that during the Second World War weather information was used more to inform government bans on central heating rather than day-to-day running of grids: Walker, *History of the Meteorological Office*,

with the same commercial service provided for any other sector—much the same situation as 1929.

This section has shown a pre-war gas industry that was fairly resilient to the vagaries of the weather due to the redundancies built into the system and the ability to respond to local circumstances based on local knowledge. Where climatological information was used, it was mostly as a diagnostic tool for measuring efficiency or product loss, rather than as a centralised control mechanism. The immediate post-war industry suffered from many of the problems experienced by other industries at the time—shortage of manpower and the increasing cost of coal. The winter of 1947 further stretched the gas industry, although the fact that gas could be delivered at a reduced pressure meant that most gas customers could at least rely on some form of service, as opposed to electricity customers who were often forced to experience blackouts. Post-war shortage helped set the scene for a systematic program of rationalisation that would begin upon nationalisation in 1948.

Nationalisation and Rationalisation

Traditionally, gas distribution could be considered a patchwork of largely independent supply systems between local gas works and consumers, with little transfer of product taking place between separate undertakings. In the immediate post-war era, only a few undertakings operated at a scale that would make more formalised weather-based forecasting economic. Amongst these was the Gas Light and Coke Company, which controlled a considerable area north of the Thames and directly transitioned into the North

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286–87. In addition, there is little mention of weather in gas textbooks at the time: R. N. Le Fevre, *Gas Distribution Engineering: The Principles for Students* (London: Walter King, 1948); Norman S. Smith and R. N. Le Fevre, *Domestic Utilization of Gas | Parts 1 & 2* (London: Walter King, 1947); John Terrace, *Notes on Gas Distribution for Gas Engineers and Students*, 1st ed. (London: Ernest Benn Limited, 1952)

Thames Gas Board upon nationalisation in 1948.[14] In a 1950 seminal paper, D. G. Rose, Coke Manager of the new North Thames Gas Board, undertook an analysis of consumption trends within the area going back to 1938 to find an empirical formula relating gas consumption to atmospheric temperature.[15] He was motivated both by a desire to manage production more efficiently, as well as to undertake analyses of the system under standardised conditions in order to inform debates regarding peak demand and variable tariffs, echoing similar motivations within the electricity industry at the time.

For his analysis Rose used averaged 24-hourly temperature readings from a single dry-bulb thermometer set up within a Stevenson screen in Fulham, which was approximately at the geographical centre of the company's area of operation. Rose briefly examined other meteorological variables, such as sunshine, wind, and rain, but deemed these factors "not worth while to take into account for anything more than minor adjustments in stock control." This contrasted to the approach of the electricity industry, which incorporated a range of weather variables at this time. Simply plotting the daily gas consumption against daily temperature gave a scatter that was too wide for providing useful forecasts (Fig. 10, A). To reduce the scatter, Rose experimented with processing the atmospheric temperature into a more useful variable known as "effective temperature." For example. taking an average of the atmospheric temperature and an expected seasonal temperature helped account for psychological and thermal lag effects, reducing scatter considerably (Fig. 10, B). However, Rose's favoured recipe for effective temperature involved raising a temperature divergence to the power of 1.4 (see appendix C), which he claimed accounted for the non-linear heat loss from houses due to convection air currents (Fig. 10, C).[16]

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[14] H. J. Escreet, "A Survey of Gas Distribution Practice," Communication (1, Grosvenor Place, London: Institution of Gas Engineers, August 1949), IGE_1949_337_151, National Gas Archive.

[15] Rose, "A Background to Some Economic Problems in the Gas Industry."

[16] This non-linear relationship was later attributed by one observer to families using their gas ovens as space heating: Sir Kenneth Hutchison, *High Speed Gas: An Autobiography* (Duckworth, 1987), 172–73.

Interestingly, Rose believed that weather forecasts were not yet reliable enough to form the basis of operational procedure, and instead advocated for using historical climate data to calculate the probabilities of temperatures and loads at specific times of year. To this end, he examined a Meteorological Office climate record at Oxford going back to 1815 and extrapolated the temperature readings to Fulham, constructing probability graphs to inform decision making.[17]

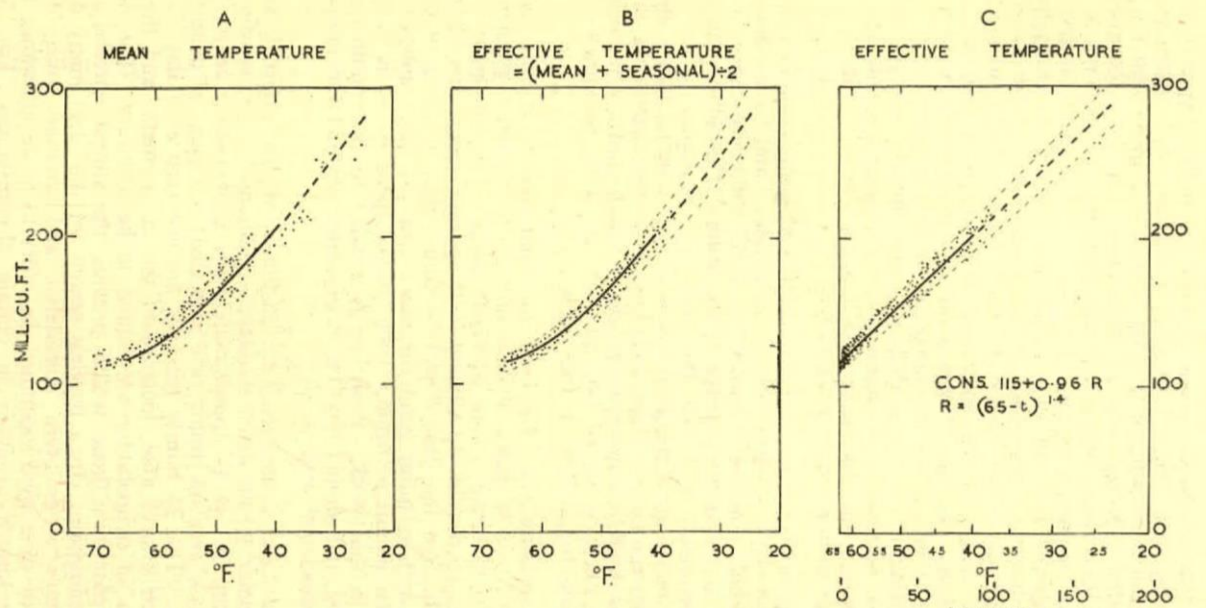

FIGURE 5—*Relationship Between Weekday Gas Consumption and Atmospheric Temperature in* 1938.

Figure 10. Relationship between weekday gas consumption and three different calculations of temperature. (A) shows the relationship with the actual mean daily temperature, (B) shows the relationship with the average of the mean and seasonal temperature, and (C) shows the relationship with the divergence from 65°F to the power of 1.4. The dotted lines represent 95% confidence intervals.[18]

The response to Rose's paper was overwhelmingly positive, but also demonstrated the heterogeneity of techniques for dealing with the weather and resistance to

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[17] It is interesting to note that the possibility of climatic changes does not seem to have entered Rose's considerations, reflecting a static view of climate that was only just starting to be challenged.

[18] Rose, "A Background to Some Economic Problems in the Gas Industry," 16.

standardisation. J. E. Davis of the South Eastern Gas Board, whose territory also included parts of London, found Rose's power relationship highly convincing. In contrast, J. D. Dyde of the Eastern Gas Board queried whether gas consumption followed similar patterns between urban and rural areas., presenting data from Huntingdon and Maldon as evidence, and preferred to rely on individually calculated linear relationships for specific months rather than a generalised consumption–temperature relationship. In this latter view he was joined by F. O. Hawes of Tottenham, who also queried the validity of pre-war data for forecasting in 1950. Both Dyde and Hawes were unconvinced by Rose's convection-based explanation for his power law. In response, Rose was quite accommodating of these differences: "Method is very much a matter of opinion, and it is not to be presumed that there is any one method that will be found superior to others in all circumstances."[19] Indeed, even within undertakings, forecast methodologies could vary from region to region depending on the nature of consumers, whether they be industrial or domestic, urban or rural.[20]

The Gas Light and Coke Company was an exceptionally large undertaking, and its operation would inform the large-scale area boards that would succeed it upon nationalisation. Many of the pre-nationalisation gasworks were small family firms often using what were considered outdated or inefficient manufacturing techniques, the smallest serving as few as 100 individual customers. Nationalisation of the gas industry in 1948 led to a long-term consolidation in the number of works in the name of increasing efficiency, declining from 1050 in 1949 to 341 in 1962. Of the 341 gasworks kept by the industry, only 74 supplied over 73 percent of manufactured gas.[21] Nationalisation vested decision-making power into

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[19] Rose, 46.

[20] C. E. Mills, "Predicting Gas Demand in the Area of the East Midlands Gas Board" (Institution of Gas Engineers, Midland Section, January 1964), P12532, National Gas Archive.

[21] Davis, *Blue Gold*, 97; Hutchison, *High Speed Gas*, 161; Williams, *A History of the British Gas Industry*, 59.

12 area boards, which by the end of the 1950s were showing a renewed interest in the acquisition of weather information for everyday operational procedure. In its 1960 annual report, the Meteorological Office stated that “There has been a growth in the demand for information from local gas authorities and now, in addition to routine forecasts supplied to key operation centres in each Gas Board area, forecasts are supplied to individual gas works in many areas.”[22] Considering that domestic gas consumption in 1960 was below 1946 levels, a simple rise in consumer demand and any resultant pressures can be ruled out as the cause.[23] It is probable that this growth in demand for weather information resulted from the accelerated development and centralisation of grid control, with a swathe of new regional control rooms opening in the late 50s and early 60s, as well as the concentration of manufacturing capacity into a smaller number of larger gasworks.[24] As gas distribution networks became larger and more integrated, the potential for cost savings through accurate forecasts increased. Likewise, as the power to alter production shifted from local gasworks engineers, who often had an intuitive feel for how their area would respond to weather, to centralised controllers or managers at large regional gasworks, demand for more formalised weather information grew.

During 1960–65, a convergence of factors increased consumer demand for gas and made it more competitive against electricity, reversing a pre-1960 trend of declining domestic consumption. On the supply side, a more efficient transmission system and the introduction of cheaper oil-based manufacturing processes brought down the price of gas relative to electricity. On the demand side, restrictions on coal fireplaces through the 1956 clean air act and a nationally coordinated marketing campaign increased the sales of gas

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[22] Meteorological Office, “Met Office Annual Report,” 1961, 18.

[23] Department for Business, Energy, and Industrial Strategy, “Historical Gas Data: Gas Production and Consumption 1882 to 2019,” July 30, 2020.

[24] Francis, “Grid Control—Past, Present and Future”; Mills, “Predicting Gas Demand in the Area of the East Midlands Gas Board.”

space heating appliances. Ambitious managers, often working against the advice of engineers who were concerned with an uncontrollable peak demand, placed adverts in national journals for central heating, and this bullish sales attitude may have contributed to failures of supply during the harsh winter of 1963.[25] Nevertheless, the revival and consolidation of the industry, largely based on weather-sensitive domestic heating demand, was echoed by the development of gas-demand forecasting techniques, often building on Rose's 1950 paper. The disastrous winter of 1963 and the resultant press attention seemingly accelerated this effort.[26] The papers of the 1960s did not so much supplant Rose's methodology as provide different methodologies for calculating effective temperature for other control areas, continuing the industry's tolerance for heterogeneity. Indeed, Rose's power relationship continued to be used by the North Thames Gas Board until at least 1981.[27]

This section has shown how intermingled factors moderately increased the demand for weather information by gas supply authorities before the introduction of natural gas. Intermittent shifts in consumer demand towards space heating, skyrocketing coal prices,

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[25] Williams, *A History of the British Gas Industry*, chap. 14; Berrisford, "The Relation between Gas Demand and Temperature," June 1, 1965; Hutchison, *High Speed Gas*, 172–74. Hutchison writes "the industry as a whole would not support central heating as an objective and my old company, still very much under the influence of its engineers, was reluctant to take on what it saw as an uncontrollable peak load [i.e. demand]. So I decided to go it alone and in 1959 there appeared our first advertisement for central heating in a national journal." (p. 173). This triumph was quickly followed by the harsh winter of 1962, where again the energy systems could not supply their customers even if the systems had functioned perfectly in the winter conditions. Hutchison, later knighted, went on to have a very successful career. However, some members of the public were furious at the sorts of actions he had taken, reflected by letters to The Times that asked why the utilities industries were unable to satisfy the demand that they themselves had created: E. Mendelsohn, "Not Enough Power," *The Times*, January 17, 1963, The Times Digital Archive; E. B. Simmons, "Warmth And Light," *The Times*, January 29, 1963, The Times Digital Archive. It should be noted that public anger over the winter of 1962–3 in *The Times* was directed elsewhere as well – especially at union strikes. Hutchison was only one example when it came to managers overriding the concerns of engineers in an era when tensions between management and staff were already fraught.

[26] Mills, "Predicting Gas Demand in the Area of the East Midlands Gas Board"; Berrisford, "The Relation between Gas Demand and Temperature," 1965; R. Kerr, H. G. Berrisford, and George M. Polanyi, "Demand Forecasting," Study Sessions (Brighton: The Gas Council, March 22, 1966), 7864, National Gas Archive.

[27] B. T. Tickle, "The Use of Weather Information in the Gas Industry" (Welman House, Altrincham: Manchester District Junior Gas Association, May 2, 1984), 5, P00305, National Gas Archive.

and wartime shortage of manufacturing plant coincided with and reinforced efforts to consolidate and capital-optimise the gas supply system. A patchwork of largely independent supply systems gave way to much larger regional interconnected networks, reducing the need for storage and increasing the need for weather-based demand forecasting. The more efficient system was better able to attract customers back from electricity, meaning that by the early 1960s gas could be said to be a growing industry again. However, this growth was but a prelude to the meteoric expansion induced by a glut of natural gas from the North Sea (Fig 1). This expansion would transform the system, leading to a new demand for increasingly specialised weather data.

The Natural Gas Transition

With the development of steel pipes in the 1920s allowing long-distance transmission, natural gas was able to become a substantial component of the United States' energy mix in the 1920s.[28] British interest in natural gas coincided with other post-war efforts to reduce the gas industry's reliance on expensive high-grade coal. Most of these projects were led by the Gas Council—a national co-ordinating and research body on which the chairmen of the area boards sat. For example, the Gas Council played an important role in instigating the world's first ship-borne transportation of liquefied natural gas. The ship *Methane Pioneer* imported Britain's first natural gas from the US in a 1959 trial, and commercial liquefied natural gas imports from Algeria began in 1964 (Fig. 9).[29] Although not revolutionary in its volume, the importation of liquefied natural gas laid many of the technological and institutional foundations for what was to come, beginning the construction of a more centralised distribution system and demonstrating to the area boards the advantages of a more centralised approach. Partly as a result, the 1965 Gas Act

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[28] Davis, *Blue Gold*, 4.
[29] Williams, *A History of the British Gas Industry*, 145.

empowered the Gas Council to buy and sell gas, putting it on an equal footing with the area boards. This institutional centralisation was completed by the 1972 Gas Act, which merged the Gas Council and area boards into a single entity: the British Gas Corporation.[30] It should be noted, however, that the British Gas Corporation inherited the decentralised structure of the area boards, and the British Gas regions retained much autonomy in practice, including in areas such as weather-based demand forecasting.

Since 1948, the Gas Council and its constituent area boards enjoyed an effective monopoly over the British gas production and supply. However, this monopoly came under threat in 1962 when Shell, Esso and BP announced a joint survey of the North Sea in an exclusive partnership that barred the Gas Council from entry. Sir Kenneth Hutchison, the deputy chairman of the Gas Council at the time, noted that his “disappointment was intense,” a feeling that only grew as the Gas Council’s repeated overtures to the group were rejected.[31] As a result, the Gas Council set up its own competing exploration group with three American oil companies, Amoco, Amereda and Texas Eastern. Both exploration groups found promising geology for exploitable gas deposits, and the Gas Council, newly empowered by the 1965 Gas Act to buy and sell gas, was allocated a substantial portion of the sea floor for exploration and exploitation. The first of many strikes were made in 1965. Hostilities were renewed when BP attempted to sell its gas to the Gas Council at retail value, a price that the Gas Council, with its insider knowledge of the costs involved, was not willing to pay. As the only buyer in Britain by law, the Gas Council was eventually able to force the hand of the oil companies, effectively establishing a national monopsony to complement the national monopoly it already had.[32]

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[30] Davis, *Blue Gold*, 100–101.

[31] Hutchison, *High Speed Gas*, 235.

[32] Davis, *Blue Gold*; Richard Pryke, *The Nationalised Industries: Policies and Performance Since 1968* (Oxford: Martin Robertson, 1981), chap. 2.

In order to justify advantageous licencing that blocked competition, the Gas Council had to demonstrate to the government that it could distribute the glut of gas to consumers with haste and efficiency. The government and Gas Council had agreed that the new resource was to be exploited as quickly and extensively as possible in order to induce economic growth, and the Gas Council soon felt the weight of its promises, aggressively marketing gas to industry and even selling at a loss in order to increase the size of the market. There was simply too much gas and not enough customers. Seeing the political benefits, the government at the time was supportive of a policy that gave households cheap access to gas. This period of problematic plenty required a whole new distrubution system. In 1965 the Gas Council started development of the National Transmission System—an unprescedented network that was connected nationally via large-diameter high-pressure pipes and compressors (Fig. 11). Reflecting the pressing need of the Gas Council, this huge infrastructure programme was largely complete within a decade.[33]

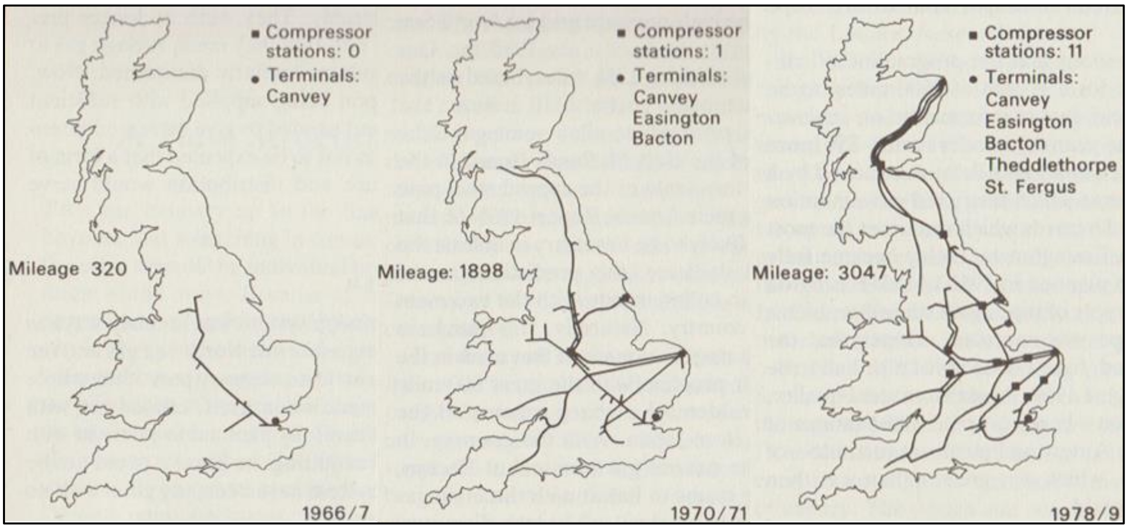

Figure 11. Rapid development of the national gas high pressure transmission system[34]

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[33] Davis, *Blue Gold*; Williams, *A History of the British Gas Industry*.

[34] Williams, *A History of the British Gas Industry*, 226–27.

Traditionally, the transfer of weather information between the Meteorological Office and gas industry had been a highly localised process between area boards and their respective local weather centre. The format (e.g. type of information and time interval) of these forecasts was dependent on specific local needs and preferences.[35] With the advent of the National Transmission System, the requirement arose for demand forecasts on a national scale, and therefore a standardised format for weather forecasts that could be integrated by national control. In addition, as part of the capital-optimisation process, the National Transmission System imposed a new level of uniformity on the production of gas. Simply put, North Sea gas production could not be economically turned off and on like a tap, only attenuated slightly. This completely transformed the problem of peak load on the system. Formerly, it was only necessary to consider the "tip" of the demand curve, as regional gasworks could be switched on or off to offset changes; as long as there were enough gasworks to meet peak demand, the system would be able to quickly adapt to changes in consumption given plentiful gas manufacturing material. However, now gas network controllers had to provide suppliers, most of which were not part of the nationalised gas industry, with reliable demand forecasts at the beginning of each day, and daily and yearly swings in demand as well as forecast errors would have to be accommodated for with regional storage and liquefied natural gas backup supplies.

Suddenly the system was much more sensitive to hour-by-hour weather changes. Frank Lyness, the manager of British Gas's Operational Research Department, wrote in 1984 that national investment in regional storage could be reduced by an estimated £50m if the standard deviation of the percentage errors of day-ahead forecasts were reduced from five

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[35] J. L. Piggott, "The METGAS System: A Computerised System for Receiving, Storing and Using Weather Forecasts to Predict Short Term Gas Demand" (North Thames House, Staines: London & Southern Junior Gas Association, December 1981), 2, P01229, National Gas Archive.

to four percent.[36] In addition, the operational use of such storage was expensive; liquified natural gas had a habit of boiling off, and high-pressure storage required the use of compressors.[37] Accurate short-term forecasts increased everyday efficiency as well as decreasing long-term construction costs. The contrast to the comments of J. H. Dyde about how the pre-war gas engineer "worried little about the vagaries of the weather" could not be starker.[38] The weather had transformed from a background feature to which only some gas engineers paid attention, into an integral variable that could be exploited for millions of pounds of savings.

At the turn of the 1970s, two scientists at the Applied Computing Group of the British Gas Corporation's London Research Station, P. S. Turton and M. D. Harper, were set to the task of evaluating weather forecasts for short-term gas demand prediction: "With the advent of natural gas, the increasing sensitivity of domestic loads, and the complex economics of future storage and operating policies, there is a need to predict short-term gas demands with accuracy and confidence."[39] In a 1973 paper, Turton and Harper established the "METGAS" format that would become the standard weather forecast for the industry (Fig. 12). In 1973, METGAS forecasts were issued every four hours from the Meteorological Office, giving a twenty-four-hour forecast of temperature at two-hour intervals and

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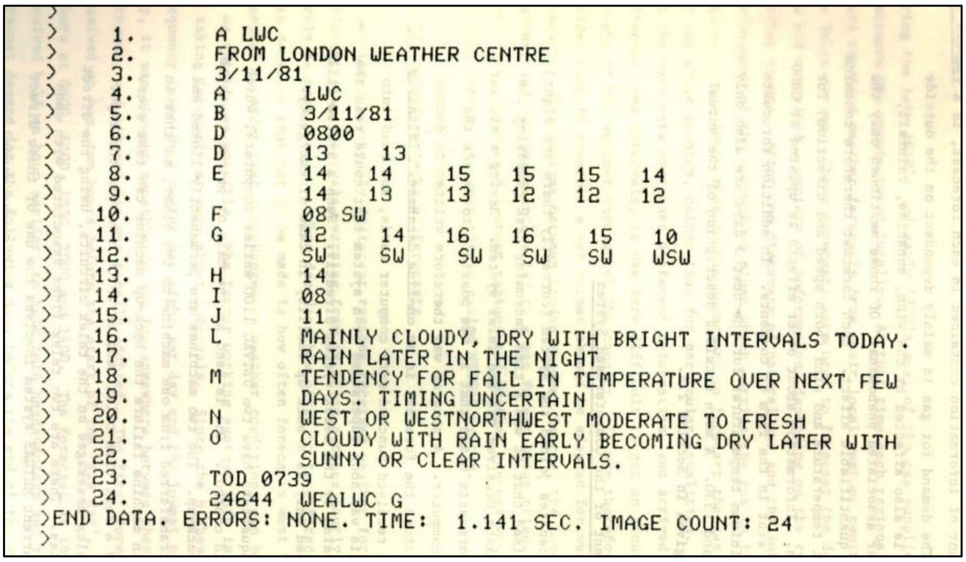
[36] E. H. M. Badger and Frank Lyness, "A National Survey of the Relative Severity of Past Winters with Particular Reference to Gas Storage Policy," Operational Research (Gas Council, 1969), 18256, National Gas Archive; Frank Lyness and E. H. M. Badger, "A Measure of Winter Severity," *Applied Statistics* 19, no. 2 (1970): 119; Lyness, "Gas Demand Forecasting."

[37] British Petroleum, *Gas Making & Natural Gas*, chap. 18; Tiratsoo, *Natural Gas*, chap. 10. Liquified natural gas stored underground can boil off can boil off at 0.45% per day This volatility contrasts with coal. According to a 1949 coal distribution textbook, the loss of energy from coal stored in the open is about only about 3–5% per annum: A. E. Minns, "Some Considerations on the Storage of Coal," in *Coal: Production, Distribution, Utilisation.*, ed. P. C Pope, 1st ed. (London: Chapman and Hall Ltd for Industrial Newspapers Ltd, 1949), 115–16. This material change, which made energy storage in the gas distribution system less efficient, contributed to the increase in weather sensitivity within the gas industry.

[38] Rose, "A Background to Some Economic Problems in the Gas Industry," 41.

[39] P. S. Turton and M. D. Harper, "Weather Forecast Evaluation and Its Role in Short-Term Gas Demand Prediction," Communication (17, Grosvenor Crescent, London: Institution of Gas Engineers, November 1973), 1, IGE_1973_907, National Gas Archive.

windspeed/direction at four-hour intervals. In addition, mostly qualitative three-day forecasts were issued twice daily. Two-hourly demand and weather data were sent to the London Research Station via telex and stored on a Univac 1106 computer. During archiving, the weather data would go through a process of quality control where discontinuous or unseasonal temperatures would be checked for. Data storage and retrieval was done via the STARE program, which included a bespoke user-friendly coding language for data analysis.[40]



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>
>     1.      A LWC
>     2.      FROM LONDON WEATHER CENTRE
>     3.      3/11/81
>     4.      A       LWC
>     5.      B       3/11/81
>     6.      D       0800
>     7.      D       13    13
>     8.      E       14    14    15    15    15    14
>     9.              14    13    13    12    12    12
>    10.      F       08 SW
>    11.      G       12    14    16    16    15    10
>    12.              SW    SW    SW    SW    SW    WSW
>    13.      H       14
>    14.      I       08
>    15.      J       11
>    16.      L       MAINLY CLOUDY, DRY WITH BRIGHT INTERVALS TODAY.
>    17.              RAIN LATER IN THE NIGHT
>    18.      M       TENDENCY FOR FALL IN TEMPERATURE OVER NEXT FEW
>    19.              DAYS. TIMING UNCERTAIN
>    20.      N       WEST OR WESTNORTHWEST MODERATE TO FRESH
>    21.      O       CLOUDY WITH RAIN EARLY BECOMING DRY LATER WITH
>    22.              SUNNY OR CLEAR INTERVALS.
>    23.      TOD 0739
>    24.      24644  WEALWC G
>END DATA. ERRORS: NONE. TIME:  1.141 SEC. IMAGE COUNT: 24
>
```

Figure 12. A typical METGAS telex from 1981. Section D shows the actual temperatures from the last couple of two-hourly periods. Section E shows two-hourly temperature forecasts for the next twenty-four hours. Likewise, section G shows the four-hourly windspeed and direction. Section F shows the actual windspeed followed by the direction. Section H onwards were only issued twice daily at 8am and 3:30pm, showing minimum and maximum forecast temperatures for the coming days as well as comments.[41]

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[40] Turton and Harper, “Weather Forecast Evaluation and Its Role in Short-Term Gas Demand Prediction.” An example of the STARE coding language: REC HLD DAYS 010772 to 290872 ANAL. This code places two-hourly load data from 1.7.72 to 29.8.72 into a set storage area; ANAL calls a user-written program that analyses the data.

[41] Piggott, “The METGAS System: A Computerised System for Receiving, Storing and Using Weather Forecasts to Predict Short Term Gas Demand.”

Turton and Harper outlined two programs that linked into STARE. The first analysed a database of past weather forecasts and actual weather data 1971–73 in order to assess the nature and likelihood of weather forecast errors.[42] The second program, named "GASFOR," undertook daily and weekly national gas demand predictions through linear regression (see appendix D). Daily GASFOR forecasts were produced at 8:00am each day for the following 24 hours. The motivations behind such a program were made clear in the paper: "The nature of the current supply position requires several hours' notice to the suppliers and improvement in predictions can reduce storage requirements and increase the security of the system." North Sea gas and the associated changes to the supply system were driving this development and attempts at standardisation in demand forecasting. Like earlier forecast methods, in 1973 GASFOR only incorporated one derived meteorological variable—effective temperature. This variable was derived from a demand-weighted average temperature given from eight METGAS weather stations. Simply put, the effective temperature was calculated as a weighted average between the temperature on the day and the temperature the day previously—much simpler than the calculation used by Rose in 1950.[43] Other variables, such as wind, sunshine, and humidity, were considered to be "statistically insignificant" on all but the most extreme days. This reflected the domestic use of gas as being primarily for heating purposes, and again contrasts strongly with the electricity industry where other parameters such as wind and daylight illumination had been used since the 1940s.[44]

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[42] Turton and Harper, "Weather Forecast Evaluation and Its Role in Short-Term Gas Demand Prediction," 8–13.

[43] Piggott, "The METGAS System: A Computerised System for Receiving, Storing and Using Weather Forecasts to Predict Short Term Gas Demand"; J. L. Piggott, "Short-Term Forecasting at British Gas," in *Comparative Models for Electrical Load Forecasting*, ed. E. D. Farmer and Derek W. Bunn (John Wiley & Sons, Ltd, 1985).

[44] Turton and Harper, "Weather Forecast Evaluation and Its Role in Short-Term Gas Demand Prediction," 13–24.

Unfortunately for the gas industry, only using a derived temperature variable would prove insufficient for forecasting demand during the gales of the 1978–9 winter.[45] This event led to calls within the industry to introduce a “wind chill factor” into national and regional forecasts.[46] In the event, wind chill, a variable based on windspeed and temperature that only became statistically significant during times of extreme weather, was only introduced into national forecasting sometime during 1983–90, more than a decade after national forecasting using derived temperature alone.[47] Temperature and wind would remain the only two weather variables used in national short-term gas demand forecasting until at least 2016.[48]

The 1980s also led to the partial introduction of mathematically complex “Box-Jenkins” statistical methods in order the analyse system demand and relate it to weather variables, although there appears to have been resistance from many control room staff on the basis that the methodologies were overcomplex. Frank Lyness, the manager of British Gas’s Operational Research Department and an advocate for Box-Jenkins methods, admitted in 1984 that the problems of gaining acceptance included “Difficulties of explaining the structure of the model in qualitative terms, particularly to shift staff.”[49] There also appears to have been a divide between shift staff and management in terms of priorities, with shift staff being more interested in avoiding headline-drawing failures than improving efficiency:

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[45] A. C. Swift, “The Effect of a Chill Factor on EMGAS Demand Models” (Solihull: Midland Junior Gas Association, January 11, 1983), 1, P02776, National Gas Archive.

[46] British Gas Planning Department HQ, “Temperature/Demand Methodology for Planning Purposes: The TD76 Code of Practice” (British Gas plc, November 1987), 48, Joint Office of Gas Transporters Website.

[47] Frank Lyness and I. J. Whitting, “Gas Demand in Severe Weather—Aspects of Forecasts and Planning: A National View” (Institution of Gas Engineers, London & Southern Section, November 1979), P01208, National Gas Archive; Tickle, “The Use of Weather Information in the Gas Industry”; Lyness, “Gas Demand Forecasting”; R. Fildes, A. Randall, and P. Stubbs, “One Day Ahead Demand Forecasting in the Utility Industries: Two Case Studies,” *The Journal of the Operational Research Society* 48, no. 1 (1997): 15–24.

[48] “Gas Demand Forecasting Methodology” (National Grid House, Gallows Hill, Warwick, CV34 6DA: National Grid Plc, November 2016).

[49] Lyness, “Gas Demand Forecasting,” 13.

"Their overriding concern to avoid large errors, especially at high levels of demand, rather than merely to improve the average accuracy of forecasts, is not surprising but is easily overlooked."[50] Finally, staff were annoyed that they still had to intervene with these complex models in order to account for influences that were not included in the model such as holidays: "Sophisticated models tend to be regarded by their users as "black boxes" which should always produce good forecasts without human intervention."[51] In reality, Box-Jenkins modelling appears to have had less impact than its hype suggested. Even while advocating the methods, Lyness wrote that "the model, apart from the better representation of the noise term, is formally equivalent to using effective temperatures and simple regression."[52] This equivalence perhaps contributed to the eventual abandonments of these complex techniques. By 2012 it appears that national forecasts had moved back to a simpler regression-based model.[53]

Although natural gas led to the development of nationwide demand forecasting, the importance of regional forecasts did not diminish, and there was very active development in this area in the wake of the natural gas revolution.[54] The rules governing the national transmission system meant that the amount of gas each region could draw from the grid were absolutely dependent on these daily weather-influenced forecasts, with financial repercussions if the forecast was incorrect. Each day regional grid controllers were required to nominate the volume of gas they required from the national transmission system to meet the next day's demand. Once the nomination was made, the possibility of revision

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[50] Lyness, 13.

[51] Lyness, 13.

[52] Lyness, 12.

[53] "Gas Demand Forecasting Methodology" (National Grid House, Gallows Hill, Warwick, CV34 6DA: National Grid Plc, 2012).

[54] R. A. Steel and C. W. Stubbs, "Forecasting ~ Why and How" (Glasgow: Institution of Gas Engineers, Scottish Section, January 20, 1982), P13270, National Gas Archive; R. Edwards, "The Forecasting of Gas Demand" (Yorkshire Gas Association, May 12, 1982), P01886, National Gas Archive; Swift, "The Effect of a Chill Factor on EMGAS Demand Models"; Tickle, "The Use of Weather Information in the Gas Industry"; M. J. Gillet, "Forecasting the Demand for Gas" (Gould Street, Manchester: Manchester District Junior Gas Association, February 6, 1985), P00313, National Gas Archive.

was limited by rules set down by central control through contractual agreements with North Sea suppliers. Beyond this, regional controllers had the option to interrupt the gas supply of customers on cheaper interruptible contracts, a revenue-affecting decision that would also be dictated by weather-based forecasts.[55] It is clear that the advent of natural gas made the system more financially sensitive to atmospheric changes, a sensitivity that led to developments in both short-term and long-term forecasting, operations, and planning.

Longer-term Planning

As with short-term forecasts, the need to forecast the probabilities of extreme winters became more pertinent at with the advent of natural gas, as the need to forecast weather under a new economic regime extended from the "tip" of the demand curve to the "bulge," and new storage became essential to cushion against changes in demand. Engineers often divided the storage into two categories. Firstly, storage for economic reasons that allowed the National Transmission System to have a supply capacity less than the peak daily demand. Secondly (and it was usually mentioned second) storage that was required to provide security against system failures or incorrect forecasts. It was British Gas policy to have a supply capacity to accommodate for a "1 in 50" winter and a "1 in 20" day (the latter referring to the daily demand for gas that would be expected to be exceeded once every twenty years), which guided much of the work done in the area. It seems that these 1 in 50 and 1 in 20 figures were fairly arbitrary—a Gas Council report from May 1971 struggled to grapple with what "security" was worth beyond monetary terms: "The costs of insecurity are, basically, the loss of revenue caused by not supplying, and the cost of reconnection following an interruption, both of which are fairly well defined, together with less tangible costs that, although very important, cannot currently be assessed on a

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[55] Gillet, "Forecasting the Demand for Gas."

quantitative basis."[56] Nevertheless, the British Gas Corporation and its constituent regions were very interested in understanding the likely severity of future winters in order to minimise investment in storage infrastructure.

Under the auspices of the Gas Council in May 1969, E. H. M. Badger of the London Research Station and Frank Lyness of the Gas Council's Operational Research Department produced a 103-page report surveying the severity of past winters (measured in degree-days below 37°F) with special regard to gas storage policy, drawing on long-term readings from seventeen meteorological stations. In their report, Badger and Lyness considered the effects of long-term climate changes: "If predictions about the probability distribution of degree-days in future winters are to be attempted, it is very dangerous to neglect an analysis of trends of past data."[57] Accordingly, Badger and Lyness examined what they saw as the longest set of temperature records available to them, those of Oxford that were continuous since 1853 (Fig. 13).[58] Badger and Lyness demonstrated a knowledge of meteorological thought regarding long-term climatic changes, referencing the climatological work of Hubert Lamb and Gordon Manley, and they highlighted the abrupt change to mild winters occurring around 1895.[59] However, the Gas Council researchers found cause-effect explanations for this drift to be unsatisfactory and found it difficult to model the long-term climatic trend statistically, therefore deciding that for the purposes of forecasting they would consider the temperatures to follow a random distribution. For

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[56] D. J. Clarke, G. S. Cribb, and W. J. Walters, "The Philosophy of Gas Storage" (Solihull: Institution of Gas Engineers, May 1971), 13–14, IGE_1971_845, National Gas Archive.

[57] Badger and Lyness, "A National Survey of the Relative Severity of Past Winters with Particular Reference to Gas Storage Policy," 8.

[58] For more on this dataset: Stephen Burt and Tim Burt, *Oxford Weather and Climate Since 1767*, Illustrated edition (Oxford, United Kingdom: Oxford University Press, 2019). Although meteorological measurements at Oxford go back much earlier, it was only in 1853 that temperature began to be measured with a screened thermometer.

[59] Gordon Manley, "The Mean Temperature of Central England, 1698–1952," *Quarterly Journal of the Royal Meteorological Society* 79, no. 340 (1953): 242–61; Hubert H. Lamb, "What Can We Find out about the Trend of Our Climate?," *Weather* 18, no. 7 (1963): 194–216; Hubert H. Lamb, "Britain's Changing Climate," *The Geographical Journal* 133, no. 4 (1967): 445–66.

many calculations, Badger and Lyness used the range 1931–63 as that period followed the random distribution pattern more consistently. From these assumptions, they calculated the “average return time” of the harsh winters of 1963, 1947 and 1940 to be around 75 years, 35–40 years and just under 20 years respectively, although they made clear that these return times had considerable deviations in different parts of country. To make an estimate of the equivalent gas demands, Badger and Lyness simply assumed a linear relationship between degree days and gas storage requirements, disregarding some of the more complex relationships between temperature and demand used by some British Gas regions.

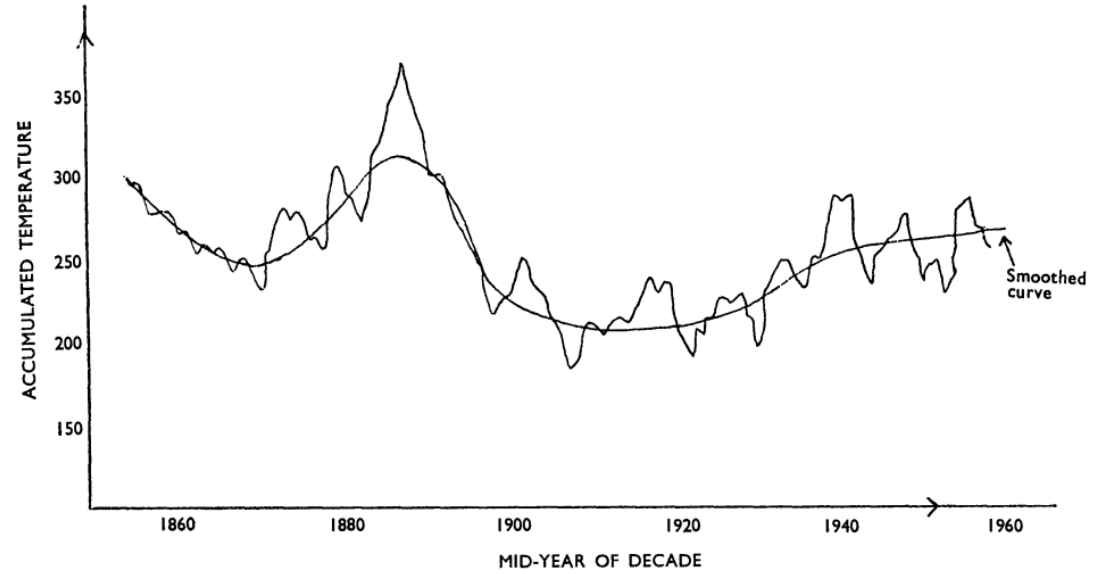

FIG. 3. Ten-year running means of accumulated temperature per winter below 37°F at Oxford.

Figure 13. Ten-year average degree days below 37°F (~3°C). The ten-year average was employed in order to smooth out fluctuations. It should be noted that a lower number of degree days corresponds to warmer temperatures.[60]

Specifying these 1 in 50 conditions was essential underpinning for other aspects of planning. Lyness was heavily involved in much of the long-term planning within the

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[60] Lyness and Badger, “A Measure of Winter Severity,” 123.

industry regarding the shaping of the National Transmission System. He was deeply intertwined with the international operational research community, being awarded the Operational Research Society's bronze medal for a paper Lyness published in 1970. Around this time, Lyness spent a period at the Massachusetts Institute of Technology under John Little, a pioneer in the field and the first person to hold a PhD in operations research.[61] Lyness's 1970 paper concerned the security of supply in a gas transmission system, attempting to calculate the probabilities of pipeline failure and the optimum positioning of storage facilities to avoid it: "Failure to supply is costly, both financially and psychologically, especially in a premium-fuel industry which is striving to increase its share of the energy market."[62] In practice, this paper represented an early application of risk analysis to the gas supply system. Lyness used American data to estimate the probability of transmission pipe failure, then constructed a range of simple models (not using a digital computer) to calculate various probabilities of system failure over time. Given many assumptions, Lyness found that the chance of supply failure in the years 1970–71 in a system with no storage was 1 in 10, which decreased to 1 in 30 if strategic storage facilities were constructed in Scotland and South Wales. Lyness made it clear in his conclusion that the models used by the Gas Council in practice were far more complex, for example incorporating the economic aspects of storage as well as the security aspects. Nevertheless, it was clear from this paper that storage helped secure the system against supply failure.

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[61] "1971 Awards," *Operational Research Quarterly (1970–1977)* 22, no. 2 (June 1971): 95–97; John R. Hauser and Glen L. Urban, "John D. C. Little," in *Profiles in Operations Research*, ed. Arjang A. Assad and Saul I. Gass (Springer, 2011), 659–76. In addition, Lyness chaired the Operational Research Society's national conference in 1981: Frank Lyness, "The O. R. Society National Conference, University of Sussex, 8–11 September 1981," *Journal of the Operational Research Society* 32, no. 8 (August 1, 1981): 745; Frank Lyness, "The O. R. Society National Conference, University of Sussex, 8–11 September 1981," *Journal of the Operational Research Society* 32, no. 5 (May 1, 1981): 426. He was also engaged with the European operational research community: Lyness, "O.R. and U.K. Natural Gas Depletion Strategy."

[62] Frank Lyness, "Security of Supply in a Gas-Transmission System," *Journal of the Royal Statistical Society: Series C (Applied Statistics)* 19, no. 1 (1970): 51.

In the late 1970s Lyness, now the Operational Research Manager at British Gas Headquarters,[63] revisited the question of long-term climate-based demand forecasting, aiming to create a consistent approach between the British Gas regions. It seems that this was partly driven by "economic and environmental pressures on the construction of LNG [liquified natural gas] facilities' that made inconsistency in approach between different regions undesirable."[64] These economic pressures were contributed to by the world oil crisis of the 1970s, which also corresponded to rocketing prices of imported liquified natural gas. In late 1978 a steering group was put together consisting of personnel from British Gas Headquarters and four of the twelve regions. One of the problems identified was that the time samples used by regions spanned from 17 years to 116 years, depending on the availability of data. The steering group recommended a standardisation on the 51 years from 1928/29–1978/79, deciding not to standardise for a longer time period due to a lack of data and "the problem of climatic trends." However, the steering group allowed heterogeneity to continue with regard to calculations of effective temperature. This section has shown how long-term forecasting of winter severity within the gas industry disregarded the arguments going on within climatology at the time. For the gas industry in the 70s and 80s, climate was synthesised to be a static (albeit stochastic) phenomenon.

Meteoric and Meteorological

This chapter has followed the gas industry as it went through the process of optimisation, first gradually through rationalisation during the 1950s, then dramatically through the implementation of natural gas during the 1970s. As the gas system became more optimised

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[63] It seems that Lyness stayed involved with British Gas until at least 1990: J McHugh, R. B. Gibbon, and Frank Lyness, "Offshore Seasonal Gas Supply," *Offshore Seasonal Gas Supply* 217, no. 10 (1990): 20–24.

[64] Frank Lyness, "Consistent Forecasting of Severe Winter Gas Demand," *The Journal of the Operational Research Society* 32, no. 5 (1981): 347–59. This paper won the Goodeve medal from the Operational Research Society: "O. R. Society National Conference, University of Bristol, 28 September–1 October 1982," *Journal of the Operational Research Society* 33, no. 12 (December 1, 1982): 1090.

and centralised, the demand for weather information grew. As the system became more integrated, the potential for savings through accurate forecasts increased. As the power to control the system passed from local gasworks directors, who had an intuitive feel for how their region would respond to demand, to regional controllers, the need arose for numerical weather forecasts and more formalised demand forecasting techniques. As a localised low-pressure system with plentiful redundancies gave way to a nationwide high-pressure system, and the ability to vary production to match daily demand faded, suddenly controllers were required to make much more accurate demand forecasts for the coming day. In contrast to the stereotypical view, new technologies and systems made the gas system more sensitive to changes in the atmosphere, not less, and to a large extent, the atmosphere was an emergent phenomenon within the gas supply system.

In response to this increased sensitivity, the industry responded in many ways that prioritised capital-optimisation and expansion rather than supply security during extreme weather. This can be seen in managers overriding the concerns of engineers by launching advertising campaigns before the disastrous winter of 1962–3. This can be seen in the lack of urgency in incorporating a wind-chill variable into national demand forecasts—a variable that only became relevant during times of extreme weather. This can be seen in management attempting to thrust complex modelling techniques on control room staff in order to improve average accuracy (and therefore efficiency) when the control room staff were more concerned about large errors and consequent system failure. On a more systemwide basis, the National Transmission System was not built to deliver all the directly supplied gas required by the UK population on a cold winter's day. The industry compensated for this by importing backup Liquefied Natural Gas, which especially required accurate atmosphere-informed forecasts due to contractual obligations and expensive storage and transport. As was said in 1981 by Frank Lyness, head of the British Gas Corporation's operational research department[65]:

> During the 1970's LNG facilities were constructed at strategic points on the NTS and more are in the process of construction and/or planned at the time of writing. As the economic justification for these facilities rests, at least partly, on the consequent reduction in the level of direct supplies otherwise needed in a severe winter Regions have found that the security of their winter supplies rests more and more on the forecasting of 1 in 50 levels of demand and on the resulting supply of LNG as a boost to direct supplies from the North Sea.

Again, the planning programme of the industry made the system more atmosphere-sensitive, not less. Meanwhile, during the natural gas bonanza, the British Gas Corporation jealously guarded its market position, suppressing prices to outcompete electricity—the corporation had the resources to make the system less sensitive to changes in the atmosphere, but expansion was the priority. More notable supply disruptions may have only been avoided because of the lack of severe winter weather—according to the Gas Council's own estimates in 1969[66] the UK is long overdue a winter with a severity comparable to 1947–8, when snow fell every day for 55 days straight.[67]

The storable nature of gas as a commodity has had a strong influence on how the gas distribution system has interacted with the atmosphere, and provides a contrast with electricity. In recent years, this storable nature has been exploited to provide a measure of

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[65] Lyness, "Consistent Forecasting of Severe Winter Gas Demand," 351.

[66] Badger and Lyness, "A National Survey of the Relative Severity of Past Winters with Particular Reference to Gas Storage Policy."

[67] This is not to say that Britain has not faced winter gas supply disruptions as of recent years: Rob Davies, "Surge in UK Wholesale Gas Prices Fuels Winter Energy Crisis Fears," *The Guardian*, September 28, 2021, sec. Business; "Britain Faces Gas Supply Crisis as Storage Runs Dry," *Reuters*, March 21, 2013, sec. UK; Tim Webb, "National Grid Appeals for More Gas as Imports Fail to Arrive," *The Guardian*, January 11, 2010, sec. Business; Terry Macalister, "Energy Security Questioned as National Grid Cuts off Gas to Factories," *The Guardian*, January 7, 2010, sec. Business.

security in a new renewable-oriented energy mix, with stored gas being used as a backup for generating electricity when weather conditions are not conducive to wind generation.[68] Many of the same questions asked by engineers building the new national transmission system in the 1970s are being asked again. What is an adequate amount of storage for security purposes? How should security be balanced against economic considerations? How does this new system cope with increased weather sensitivity?[69] Understanding the historical case studies of such decisions is essential as we look towards the future.

Chapter Four—Rain's Reign: The Atmosphere in the UK Water Industry

The provision of artificial heat and light, considered so far in this thesis through the electricity and gas industries, are essential parts of modern living, but perhaps not the *most* essential. This was most certainly an opinion found within the correspondences of the Journal of the Institution of Water Engineers in 1955[1]:

> An advertisement states that coalmining is the most important job in Britain. If the choice was yours, which would you sooner have—coalminers on strike for three months or waterworks engineers on strike for three days?

The UK water industry also exhibits more dimensions of weather-sensitivity than electricity or gas. So far, this thesis has mostly considered the atmosphere as it pertains to demand and how supply could be matched to it, not the direct effects of the atmosphere on

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[68] Chris Le Fevre, "Gas Storage in Great Britain" (Oxford Institute for Energy Studies, January 2013).

[69] "Exclusive—Rough Justice? UK Snubs Call for Gas Storage Capacity Review," *Reuters*, March 19, 2018, sec. Business News; "The Guardian View on an Energy Price Shock: A Crisis in the Making," *The Guardian*, September 20, 2021, sec. Opinion.

[1] Hector Gray, "Precedence," *Journal of the Institution of Water Engineers* 9, no. 6 (October 1955): 460.

sufficiency of supply. In contrast, this chapter considers the use of weather information by an industry where the atmosphere affects both supply and demand directly.

The UK water industry developed as a patchwork of small providers during the nineteenth century, many of which were controlled by municipal corporations that needed to sustain urban industrial and population growth. Under this system of ownership, the focus of water engineers was on long-term expansions to water supply to keep up with economic growth. As a result, engineers were most interested in long-term rainfall values in order to inform and justify system expansion; rainfall was seen as a static resource. During the 1980s, due to a complex of causes, the culture of the water industry decisively shifted, with more attention being paid to efficiency and economic savings, and comparatively less attention being paid to long-term expansions in the system. One way to achieve economic savings was to minimise the energy expenditure on pumping water by developing automated systems that relied on short-term demand forecasting—demand forecasts that in turn had the potential to exploit short-term weather forecasts. This process of commercialisation culminated in the privatisation of the industry in 1989. Again, the atmosphere changed for the water industry—hour-by-hour changes became important for the first time. A capacity crisis caused by underinvestment, manifested by the drought of 1995, where water supplies in some cases failed due to resource difficulties, brought another change in direction for the industry, leading to “reregulation” and a new focus on sufficient “headroom” (the gap between supply and forecast demand to account for errors). The drought also shone a spotlight on the concept of climate change, contributing to climate change becoming a factor when calculating headroom and long-term supply and demand forecasts.[2] Changing economic circumstances changed the way water engineers conceptualised the atmosphere, and this chapter explores this process.

Lapworth's Dilemma

The story of water in the UK has been one of coping with continuous expansion of demand, as a result of industrial growth, increasing population, and increasing individual consumption. Before the 1980s, a focus on meeting expanding demand was augmented by a municipal ethos of sustaining urban industrial and population growth, leading to a continuous search for new water sources to augment supply. Water supplies can be split into two broad categories—surface and underground. Surface sources refer to rivers, lakes, cisterns etc. Underground water can be accessed by wells or springs. Herbert Lapworth (Fig. 14), former President of the Institute of Water Engineers, highlighted the importance of the atmosphere in seeking out both types of supply in a lecture given at the Royal Meteorological Society in 1930: "The water engineer. or at least that section of water engineers concerned in seeking new sources of water and designing new schemes, is very largely dependent upon the observations and laws of meteorology, both as regards surface and underground water supplies."[3] Although Lapworth referenced the laws of meteorology, much of the data that he was interested in was climatic in nature. As a non-specialist, he probably made little distinction between meteorology and climatology.

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[2] It should be noted that this chapter does not deal with flooding in detail, keeping with the thesis theme of discussing utilities from the perspective of supplying demands. For more on flooding aspects: Alexander Hall, "The Rise of Blame and Recreancy in the United Kingdom: A Cultural, Political and Scientific Autopsy of the North Sea Rood of 1953," *Environment and History* 17, no. 3 (2011): 379–408; Hall, "Risk, Blame, and Expertise."

[3] Herbert Lapworth, "Meteorology and Water Supply," *Quarterly Journal of the Royal Meteorological Society* 56, no. 236 (1930): 271.

Figure 14. Herbert Lapworth in the 1920s[4]

Lapworth was the son of Charles Lapworth, a notable palaeontologist who became the first professor of geology at Mason Science College in Birmingham (the forerunner to the University of Birmingham). The son graduated in engineering from the same college, going on to be assistant resident engineer at the Birmingham Elan Valley water-supply scheme in 1897, which involved the construction of a 13-mile aqueduct. Although he published on his engineering work,[5] at this time Lapworth also published substantive research in his father's subject of palaeontology.[6] Somewhat combining these interests, Lapworth went on to establish a course on "engineering geology" at Imperial College London, which ran from 1910–22.[7] Through his interest in geological and palaeontological questions, Lapworth was

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[4] Torolf Hamm, "The Herbert Lapworth Club," Engineering Geology at Imperial, 2001, http://www.cv.ic.ac.uk/research/soils/engeo/lapworth.html.

[5] Herbert Lapworth, "The Construction of the Elan Aqueduct: Rhayader to Dolau," *Minutes of the Proceedings of the Institution of Civil Engineers* 140, no. 1900 (1900): 235–48.

[6] Herbert Lapworth, "The Silurian Sequence of Rhayader," *Quarterly Journal of the Geological Society* 56, no. 1–4 (February 1, 1900): 67–137.

[7] M. H. de Freitas and M. S. Rosenbaum, "Engineering Geology at Imperial College London; 1907–2007," *Quarterly Journal of Engineering Geology and Hydrogeology* 41, no. 2 (May 1, 2008): 223–28; Harold J. F. Gourley, "Dr. Herbert Lapworth," *Nature* 132, no. 3335 (September 1933): 507.

immersed in ideas of deep time and geography, which may have been reflected in his concerns in 1930 that climate was not being considered on a long enough timescale by engineers. He was most certainly not representative of water engineers at large.

In his 1930 address, Lapworth emphasised that in practice water engineers used long-term rainfall maxima and minima rather than average values, highlighting a standard used within the water industry of the "three driest consecutive years" which he indicated may be familiar to many within his audience. Lapworth defined the "three driest consecutive years" as about 80% of the average rainfall less evaporation losses, and expressed a fundamental unease with its use for reservoir construction and planning. The problem, so Lapworth claimed, was that the standard had been synthesised during the nineteenth century, which had experienced less severe droughts than during the eighteenth century, when averages could be as low as 72% of the mean. In addition, he claimed that this standard had become rigid "without any real justification" and that the storage requirements were highly dependent on local hydrological, geological, meteorological and physical conditions. Looking forward, Lapworth believed that future reservoir planning would be based on the average flows of streams or perhaps the driest year's flow—both values that were much more difficult to measure than rainfall.[8] Already in the 1930s, Lapworth, a water engineer, was considering the possibility of long-term climatic trends and how it should impact the industry's conceptualisations of the atmosphere, although in practice rainfall was largely treated by the industry as a resource with long-term stability.

Climate as a Static Resource in the 1950s

In 1930, Lapworth was interested in synthesising empirical laws between rainfall and water flows both above and below ground, but emphasised that these laws were grossly lacking

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[8] Lapworth, "Meteorology and Water Supply," 272–73.

at his time of speaking and that this would be an area of future research. As a result of this lack of knowledge, water undertakings usually used rain gauges directly to estimate minimum reliable flows.[9] Undertakings had been keeping rain gauges since at least the mid-nineteenth century (Fig. 15), and the number of rain gauges rapidly grew by the turn of the century.[10] As an example, by 1950 the Bolton Corporation Waterworks had twenty rain gauges split across its eleven reservoirs.[11] Of these, five were read daily and fifteen were read monthly in 1950, with reports being sent to central management once per month.[12] The monthly average rainfall supplying Wayoh Reservoir, with a drainage area of 3558 acres (14.4km^2), drew on a weighted average of five rain gauges. High Rid Reservoir, with a drainage area of only 245 acres (1.0km^2), only used data from a single rain gauge.[13] In addition to keeping their own rain gauges, many water undertakings, including the Bolton Corporation Waterworks, took out annual subscriptions from the British Rainfall Organization—a mostly volunteer-run network of rainfall data collection[14]—allowing them to access wider datasets.[15] Likewise, undertakings also passed on their rainfall data to the

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[9] "Yields" are defined as the greatest amount of water to be drawn from a given area during any and all periods of drought. In other words, it is the supply that can be relied upon at all times.

[10] For example, a series of rain gauges had been kept by the Bolton Corporation Waterworks at Belmont Reservoir since 1843, and data from these gauges was used for giving evidence to a parliamentary enquiry in 1847: House of Commons, *Reports from Commissioners*, vol. 9, 19 vols., 1847. These rain gauges were often placed on water undertakings' premises. For example, the rain gauge at Clowbridge Reservoir was placed centrally within the Irwell Valley Water Board's installation: Robert Wyllie, *Comparison of Water Levels at Clowbridge Reservoir Drawing No. 1*, 1:2500 (Parson's Lane, Bury Lancs: Irwell Valley Water Board, 1950), B23/Box 9, Manchester Archives Local Studies.

[11] John Ainsworth, "The Existing Sources of Supply of the Bolton Water Corporation" (Waterworks Engineer's Office, Town Hall, Bolton, January 1950), Manchester Archives Local Studies; British Rainfall Organization, "British Rainfall 1950," Annual Volume of the British Rainfall Organisation (London: Meteorological Office, 1952), 146–47, Met Office Digital Library and Archive.

[12] Bolton Corporation Waterworks, "Bolton Corporation Waterworks: Rainfall, Monthly Gauges, January 1950," 1950, B23/Box 1, Manchester Archives Local Studies.

[13] Bolton Corporation Waterworks, "Mean Rainfall January 1950," 1950, B23/Box 3, Manchester Archives Local Studies.

[14] David E. Pedgley, "The British Rainfall Organization, 1859–1919," *Weather* 65, no. 5 (2010): 115–17.This network had developed during the second half of the nineteenth century.

[15] British Rainfall Organization, "British Rainfall 1920," Annual Volume of the British Rainfall Organisation (London: Meteorological Office, 1920), xiii, Met Office Digital Library and Archive.

British Rainfall Organization, forming an important part of the organization’s national network.

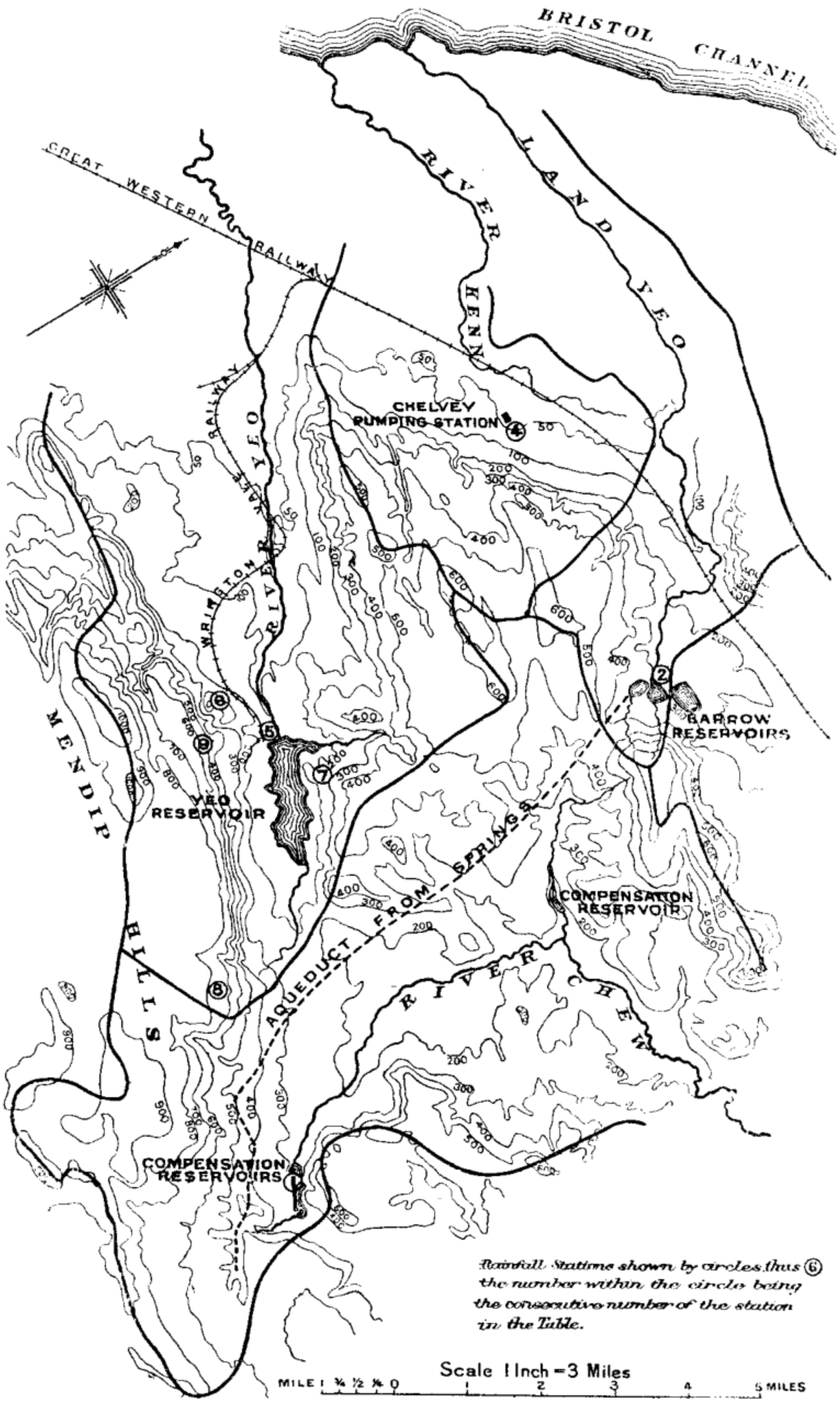

Figure 15. Positions of rain gauges of the Bristol Waterworks Company in 1913. Three of these stations had records going back to at least 1855.[16]

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[16] J A Mcpherson, "Bristol Water Works: Rainfall Statistics and Notes on Wet and Dry Cycles.," *Minutes of the Proceedings of the Institution of Civil Engineers* 194, no. 1913 (1913): 424.

The fact that rainfall data was passed to central management on a monthly rather than daily basis in the case of the Bolton Corporation Waterworks in 1950 suggests that this information was mainly being used for monitoring rather than everyday operational procedure or forecasting. Every month, managers would add up the total rainfall in a reservoir's catchment area, calculated for daily gauges by simply summing the product of the rainfall (in inches to the nearest half-inch) and the number of days that that rainfall value was taken. In addition, managers would note when reservoir overflows occurred and the rain conditions that coincided with these events. Managers were using rain data to measure the availability of water and the capacity of their current system to transfer this resource to consumers. This was essential information when considering expansions to the system—new reservoirs would need to be built where there was plentiful rainfall for supply, and reservoirs that regularly overflowed in moderate rain conditions needed to be augmented. As was said by John McPherson of the Bristol Waterworks Company at an earlier date: "Statistics of annual rainfall and of average rainfall for the longest periods obtainable are of the first importance in considering the value of any scheme for waterworks which depends upon the water resources of determinable drainage."[17]

Despite Lapworth's discussion of environmental changes in the 1930s, it should emphasised that for most practical supply purposes in the 1950s water engineers treated rainfall as a static (albeit stochastic) resource. In the pages of the *Journal of the Institution of Water Engineers* long-term rainfall records could be published with little comment.[18] In the same journal, the main complaint that water engineers had about the British Rainfall Organization's yearly publication of British rainfall was that there was such a long delay (25

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[17] Mcpherson, 421.

[18] W. N. McClean, "Graphical Record of Rainfall on the Thames Basin," *Journal of the Institution of Water Engineers* 4, no. 5 (August 1950): 432–33; "Plymouth Rainfall Records since 1893," *Journal of the Institution of Water Engineers* 9, no. 7 (November 1955): 614. Even more prized were long-term flow records, which were rarer: Frank Law and D. E. MacDonald, "The Discovery of a 50-Year Flow Record at Deep Hayes, Staffordshire," *Journal of the Institution of Water Engineers* 27, no. 6 (August 1973): 319–22.

months for 1956) for new volumes to be released.[19] These long-term records were prized for their ability to inform eyeball estimations of minima, as well as provide input data for probabilistic models for resultant flows that formed an important part of research in the post-war period.[20] Another angle of research that received much attention was the linkage of rainfall data with flows, informed by a range of meteorological, geological and topographical factors.[21] Again, most of this research was focused on informing the expansion of the network in order to cope with industrial and population growth, driven by a municipal rather than commercial ethos that reflected the strong local government role in water supply. Sufficiency and security took precedence over efficiency and cost.[22]

Money Drought in the 1970s

Both globally and in the UK, the 1970s was a decade of financial crisis. Stagflation, oil shocks, the World Food Crisis, and widespread strikes all contributed to a highly unstable economic environment. Between 1950 and 1973, UK GDP grew by an average of 3% per annum, which fell to 1.3% per annum between 1973 and 1979. Whilst the economic slowdown also slowed the demand for industrial water, diminishing expected supply

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[19] Frank Law, “Book Reviews: British Rainfall 1955,” *Journal of the Institution of Water Engineers* 12, no. 2 (March 1958): 147–48; Frank Law, “Book Reviews: British Rainfall 1956,” *Journal of the Institution of Water Engineers* 13, no. 3 (May 1959): 304.

[20] E. J. Gumbel, “Statistical Theory of Floods and Droughts,” *Journal of the Institution of Water Engineers* 12, no. 3 (May 1958): 157–84; Research Panel No. 5 of the Joint Research Committee of the Institution of Water Engineers and the Society for Water Treatment and Examination, “Recession Curves and Frequency Diagrams: Final Report of Research Panel No. 5,” *Journal of the Institution of Water Engineers* 20, no. 4 (June 1966): 231–50. It should be noted that some water engineers struggled to understand the mathematics of these models, which perhaps would have hindered their adoption: Reginald W. S. Thompson, “Communication On: Statistical Theory of Floods and Droughts,” *Journal of the Institution of Water Engineers* 13, no. 1 (January 1959): 79–80.

[21] Frank Law, “Estimation of a Reliable Yield of a Catchment by Correlation,” *Journal of the Institution of Water Engineers* 7, no. 3 (May 1953): 273–92; Frank Law, “Estimation of the Yield of Reservoired Catchments,” *Journal of the Institution of Water Engineers* 9, no. 6 (October 1955): 467–93.

[22] In the latter half of the 1960s, there was small increase in interest in new quantitative management techniques and system optimisation, although there is evidence in the responses to these papers that this interest did not always translate into practice: F. L. Ardern and N. J. Kavanagh, “Modern Management Techniques,” *Journal of the Institution of Water Engineers* 22, no. 6 (August 1968): 415–65; Peter O. Wolf, “Notes on the Management of Water Resources,” *Journal of the Institution of Water Engineers* 20, no. 2 (February 1966): 95–121.

pressures, John Hassan argues that the government's response to economic weakness was to "starve that water industry of financial resources."[23] At the same time, the 1970s represented a period of great institutional change for the UK water industry, with the Water Act 1973 bringing the culmination of several attempts to unify and integrate the fragmented and arguably dysfunctional management of the water cycle. 157 water undertakings, 29 river authorities, and 1,393 sanitary authorities passed their responsibilities onto 10 regional water authorities whose boundaries were based on river catchment areas. The regional water authorities managed the entire water cycle, including supply, sewerage, and environmental management. In addition, 32 water companies were retained in a supply role only.[24]

Times of cutbacks, increased energy costs, and the foundation of more centralised bodies focused minds on efficiency. In a 1975 technical note, the newly formed Central Water Planning Unit[25] considered the possibility of developing demand forecasting techniques along the same lines of the electricity and gas industries, which were using weather forecasts for daily operational purposes to optimise their supply systems (chapters 2–3). The preface of the report indicates that this was part of a study of "Demand Forecasting and Waste"—the motivation was clearly cutting redundancies from the system. Forecasting periods from one hour to 25 years were considered, with the introduction arguing that "although longer periods may seem of more importance to resource planner it would be a mistake to consider them in isolation, as today's information forms part of next year's

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[23] John Hassan, *A History of Water in Modern England and Wales*, 1st ed. (Oxford Road, Manchester M13 9NR, UK: Manchester University Press, 1998), 127.

[24] Hassan, chap. 5; Dennis J Parker and Derrick R Sewell, "Evolving Water Institutions in England and Wales: An Assessment of Two Decades of Experience," *Natural Resources Journal* 28, no. 4 (Autumn 1988): 751–85.

[25] The Water Act of 1973 was shortly followed by the establishment of the Central Water Planning Unit, a quango that took an advisory role in planning for the industry. The Central Water Planning Unit largely continued the emphasis on treating rainfall as a resource for supporting industrial expansion, developing new ways to synthesise river flows from rainfall data, although it also expanded its research into other operational areas: *Central Water Planning Unit* (Reading Bridge House, Reading RG1 8PS: Central Water Planning Unit, 1976).

planning data." Here we see a transition from almost exclusive interest in long-term data sets, towards more acknowledgement of short-term fluctuations in supply and demand, although the focus remains on long-term planning rather than short-term optimisation.[26]

The unit's technical note made clear the gulf between the water industry and electricity/gas when it came to demand forecasting, as well as the difficulties in acquiring data for a proper assessment of water industry methodology. The fragmentation of the industry until 1974 meant that there was no nationally co-ordinated system of demand forecasting, with individual undertakings making forecasts as deemed necessary. Demand data was rarely in a computerised form and hourly demand figures were often discarded due to their "bulky nature."[27] Later on in the report, the authors outline some other reasons for the lack of prioritisation for short-term forecasting within the industry[28]:

> In the water industry, except in circumstances where demand approaches the reliable supply from headworks, undertakers usually operate at less than the designed capacity of treatment and transmission works. Traditional design and construction procedures often provide relatively large increments of capacity because of the high civil engineering content of the works. Potable water storage equal to one day's supply is usual and systems are often self regulating, providing automatic or semi-automatic increases in plant output as soon as storage is available to receive it, thus taking care of hourly and diurnal demand variations. For these reasons the forecasting of demands a few hours ahead is relatively less important in the water industry, but information on the

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[26] Central Water Planning Unit, "Demand Forecasting for Water Related to Demand Forecasting for Water and Gas," Technical Note (12: Central Water Planning Unit, December 1975), AT 14/19, National Archives at Kew.

[27] Central Water Planning Unit, 3–4. This statement may have been covering up the fact that hourly data often was not collected at all: Institution of Water Engineers, *Manual of British Water Supply Practice*, ed. Aubrey Thomas Hobbs (Cambridge: W. Heffer, 1950), 40.

[28] Central Water Planning Unit, "Demand Forecasting," 5.

> distribution and magnitude of peak demands is nevertheless essential in the design and optimal sizing of extensions to the distribution system.

In other words, the water system did not require short-term forecasting due to redundancies in the system that could absorb unexpected weather events, with the interest of the industry being largely restricted to peak hourly demands for planning purposes. As the report indicated later, even research into hourly peak demands was minimal and publication was rare.[29] The cash-strapped environment of the 1970s and increased centralisation meant that planners paid more attention to possible efficiency measures, but in practice the focus for most water engineers remained on sufficiency.[30]

One decisive change that the 1970s did cause was to the calculation of discount rates when it came to large investments in supply expansion. Traditionally, consistent economic and population growth allowed water industry planners to justify most expansions to the system.[31] As industrial demand slowed, the justification for continuous system expansion diminished, contributing to underinvestment in new water schemes.[32] Traditional methods of forecasting long-term demand growth, usually based on some form of correlation, struggled under the new regime, as was stated in an industry-wide manual: “Latterly, growth has been erratic and overall projections would give misleading results […]. Indeed, at present it is difficult with

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[29] Central Water Planning Unit, 6.

[30] Although the willingness to use weather information for efficiency measures was not strong in the 1970s, the technical capacity to incorporate weather information continued to expand with the development of weather radar mostly for flood forecasting purposes: Central Water Planning Unit et al., “Dee Weather Radar and Real Time Hydrological Forecasting Project” (Reading: Central Water Planning Unit, November 1977), AT 14/5, National Archives at Kew.

[31] Richard Balmer, “Discounting—Its Use in Project Appraisal,” *Journal of the Institution of Water Engineers and Scientists* 29, no. 8 (November 1975): 390–401.

[32] George Archibald, “Demand Forecasting in the Water Industry,” in *Water Demand Forecasting*, ed. V. Gardiner and P. Herrington (Norwich: Geo Books, 1986), 17–23.

any method to project future demands with a high degree of confidence."[33] This underinvestment in long-term schemes was compounded by government cuts and changing management cultures that went along with the process of commercialisation that took hold during the 1980s. This process would encourage new atmospheric conceptualisations within the water industry—highlighting the potential for weather forecasts to assist in optimising systems.

Commercialisation: Short-term Forecasts Enter the Game

Although the Regional Water Authorities were required to be financially self-sufficient since their establishment in 1974, Hassan argues that for the first eight to nine years of their existence they were run with a civic rather than a commercial ethos, reflecting a statutory requirement that local government officials sit on the boards. A change in government brought a change in culture. Between 1979 and 1984 staff levels dropped by around 30%, largely as a result of new government performance-indicators. Within individual Regional Water Authorities, departments were slashed and sitting board members were reduced substantially. Against strong opposition from the Regional Water Authorities themselves, the 1983 Water Act removed the requirement for local government officials to sit on boards. The overall effect was to transform the water industry from a bloated public service into a business that was ripe for privatisation in 1989.[34]

As commercialisation took hold, efficiency measures that had hitherto been only existed in exceptionally commercially oriented undertakings resonated more widely. Amongst these more commercially minded undertakings was the East Worcestershire Water Company,

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[33] M. J. Featherstone and C. B. Buckley, "Assessment and Forecasting of Demands," in *Water Services Planning*, ed. R. A. Bailey, 1st ed., Water Practice Manuals 6 (31–33 High Holborn, London WC1V 6AX, England: The Institution of Water Engineers and Scientists, 1986), 50.

[34] Hassan, *A History of Water in Modern England and Wales*, 155–61. This civic ethos was reflected by the attitudes of many senior engineers well into the 80s: T. W. Brandon, ed., *Water Services Planning* (London: The Institution of Water Engineers and Scientists, 1986), 161.

which had begun a drive towards efficiency as a result of the efforts of engineer and manager Robert H. Burch responding to staffing shortages in the late 50s. The company was one of the first to introduce computer-based telecontrol in 1970, allowing the system to be controlled remotely and centrally—an important prerequisite for the later incorporation of short-term forecasting into operational procedure.[35] In 1980, during a period of rapid commercialisation, K. C. Marlow, the Electrical and Control Engineer of the East Worcestershire Water Company, and Frank Fallside, the Director of the Cambridge Water Company and Reader in Electrical Engineering at the University of Cambridge, presented an almost fully automated computer control system to the summer general meeting of the Institution of Water Engineers and Scientists.[36] In their introduction, Marlow and Fallside made it clear that they believed that the East Worcestershire Waterworks system was ahead of the times: "At a time when labour was still cheap, energy was inexpensive, and any form of remote operation was viewed with suspicion by most of the water industry, he [Burch] formulated and implemented a 15-year programme of modernization."[37] This programme minimized operating costs and reduced labour, exactly the sort of drive that the government was mandating at the time of publication in 1980. The system outlined by Marlow and Fallside relied upon forecasting methodology developed by the University of Cambridge's Engineering Department with the express aim of allowing "the calculation of a minimum-cost pumping schedule to meet the predicted water demand." In the early development stage, these forecasts incorporated atmospheric temperature data that marginally improved forecasting for the 48h period (Fig. 17).[38]

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[35] R. H. Burch and K. C. Marlow, "Seven Years' Operational Experience of Computer-Based Telemetry and Control Applied to a Water Supply Network," *Journal of the Institution of Water Engineers and Scientists* 32 (1978): 443–69.

[36] K. C. Marlow and Frank Fallside, "Minicomputer, Microprocessor and Telecontrol Applications to a Water Supply Network," *Journal of the Institution of Water Engineers and Scientists* 35 (1981): 517–33.

[37] Marlow and Fallside, 517.

[38] Frank Fallside and P. F. Perry, "On-Line Prediction of Consumption for Water Supply Network Control," *IFAC Proceedings Volumes*, 6th IFAC World Congress (IFAC 1975)—Part 3: Systems,

However, when developed for an operational system for the East Worcestershire Water Company, (Fig. 16) meteorological variables came to be disregarded, with the incorporation of meteorological factors being left to the experience of operators.[39]

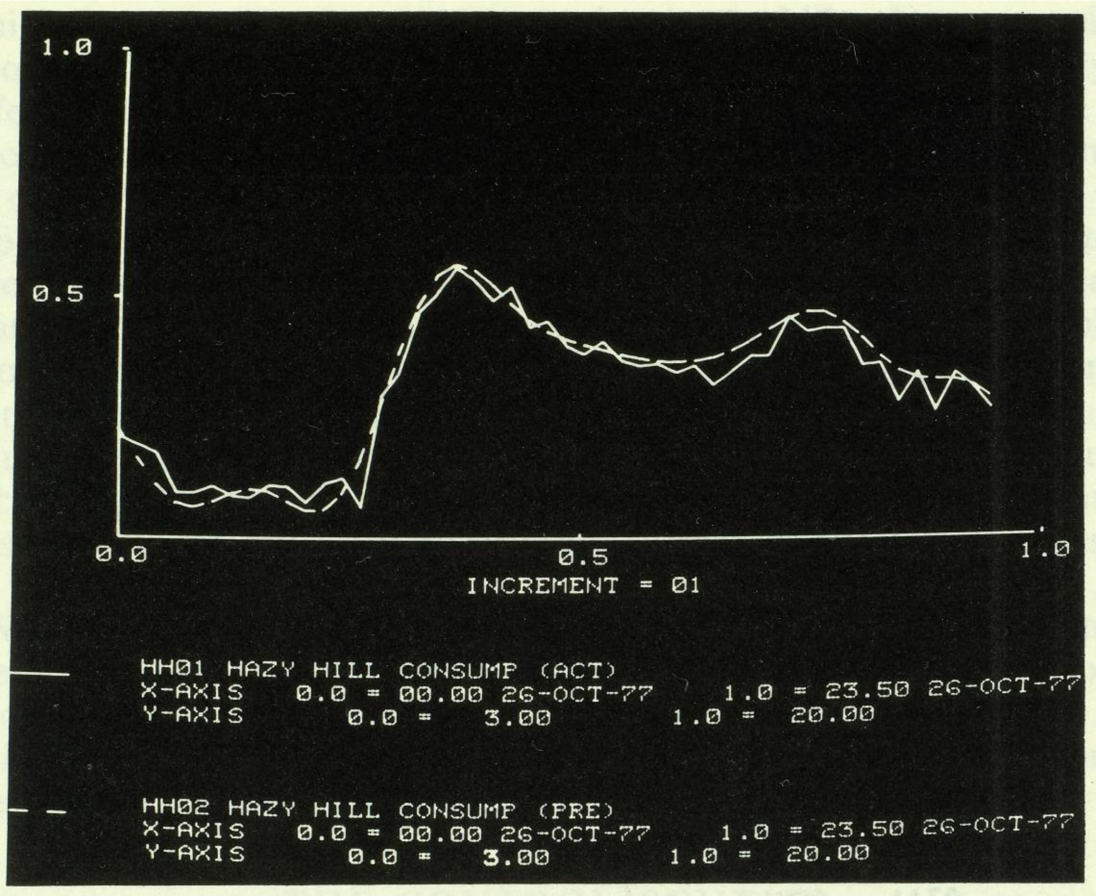

Figure 16. 24-hour forecast of consumption (dotted line) compared with actual consumption (solid line) of the East Worcestershire Waterworks.[40]

Despite new interest, it appears that for practical purposes atmospheric conditions came to be mostly disregarded in the 1980s, with short-term forecasts largely relying on the patterns of historic consumption data only.[41] Stephen Moss, a Cambridge PhD student who

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Economics, Management, and Social Effects, Boston/Cambridge, MA, USA, August 24–30, 1975, 8, no. 1, Part 3 (August 1, 1975): 396–404.

[39] Stephen Michael Moss, "On-Line Optimal Control of a Water Supply Network" (Doctor of Philosophy, Cambridge, UK, University of Cambridge, 1979), 58.

[40] Marlow and Fallside, "Minicomputer, Microprocessor and Telecontrol Applications to a Water Supply Network," 528.

[41] There is some evidence that weather information may have begun to be used for optimisation purposes by 2012, as shown by the responses to this survey: William Neale, "Hydrological

was tasked with designing the East Worcestershire Water Company's system in detail, wrote "There is sufficient experience of the system currently available to the operators to be able to correct predictions from the one week predictor in the light of (day to day) changes in the weather. Part of the future work will be to incorporate this automatically, if (and only if) sufficiently good meteorological data becomes available to us."[42] E. G. Moss and K. Howard, developing a similar system for the North Surrey Water Company, had a similar sentiment: "Ideally the [demand] forecast should include a forecast of the weather conditions over the next 24 hours, but to provide this on-line would be too expensive and cumbersome."[43] In the 80s effective exploitation of weather forecasts for operational demand forecasts was apparently beyond reach. Nevertheless, the change in industry culture had made the day-to-day weather forecast a subject of interest and study for optimisation purposes, with relevant work being done in water authorities, water companies, and academics.[44]

It is interesting to ask why the water industry did not operationalise formal techniques for incorporating weather into pump-optimisation at this time, especially when the electricity and gas industries had operationalised similar techniques decades earlier. One hypothesis is that the relationship between water demand and temperature was much more complex than that between heating demand and temperature. Water engineers in the 1980s faced

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Applications of Weather Radar: Summary of Findings and Conclusions from Survey Distributed by the Inter-Agency Committee on the Hydrological Use of Weather Radar" (Thames Water Utilities Limited, 2012).

[42] Moss, "On-Line Optimal Control of a Water Supply Network," 58.

[43] E. G. Moss and K. Howard, "Distribution System Management and Control Optimisation," in *Computer Applications in Water Supply Volume 2: Systems Optimization and Control*, 1st ed., vol. 2, Mechanical Engineering Research Studies: Engineering Control Series 4 (Letchworth, Hertfordshire, England: Research Studies Press ltd, 1988), 430.

[44] E.g. P. W. Jowitt et al., "Real-Time Forecasting and Control for Water Distribution," in *Computer Applications in Water Supply Volume 2: Systems Optimization and Control*, 1st ed., vol. 2, Mechanical Engineering Research Studies: Engineering Control Series 4 (Letchworth, Hertfordshire, England: Research Studies Press ltd, 1988), 340–42; Jack Carnell, "Short Term Demand Forecasting," in *Water Demand Forecasting* (Norwich: Geo Books, 1986), 77–85; M. J. H. Sterling and A. Bargiela, "Adaptive Forecasting of Daily Water Demand," in *Comparative Models for Electrical Load Forecasting* (John Wiley & Sons, Ltd, 1985), 213–25.

both winter and summer peaks in demand, with both peaks having very different origins. As would be expected, the summer peak resulted from factors such as garden watering and holiday activities, although these would also have a strong dependence on rainfall. In winter, water tended to freeze in pipes, causing a larger number of bursts and leaks (since household consumption was not usually measured, it was difficult to separate loss and use of water). It seems that this was a rather persistent problem, with a group from the Severn-Trent Water Authority complaining in a 1984 practice manual: "Whenever a drought or unusually cold winter spell occurs there is a tendency to search for a location or particular meteorological parameter that will illustrate how extreme the event has been. In fact, the water industry has to cope with difficult conditions rather frequently."[45] Perhaps due to these complex relationships, the improvement in demand forecast from weather forecasts may have been quite marginal, as suggested by the results of Fallside and Perry (Fig. 17). Another possibility is that weather forecasts had less value in a system where control remained localised, as opposed to gas and electricity where the systems were nationally integrated. Control over a smaller area would require much higher resolution weather forecasts, which may have been the origin of Moss's complaint that meteorological data was insufficient.[46] Finally, in the water industry short-term forecasting minimised pumping costs, which most likely increased linearly with forecast errors. This contrasted with electricity, where the costs of poor forecasting could be exponential due to the need to rely on the most inefficient power stations on the grid, and gas, where poor forecasting could break contracts with suppliers.

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[45] G. G. Archibald et al., "Consumer Requirements," in *Water Distribution Systems*, ed. Thomas Brandon, 1st ed., Water Practice Manuals 4 (London: The Institution of Water Engineers and Scientists, 1984), 85.

[46] Moss, "On-Line Optimal Control of a Water Supply Network," 58. If this was the case, this data insufficiency would be partly rectified by the development of weather radar. This development was often led by the water industry mostly for flood warning: Central Water Planning Unit et al., "Dee Weather Radar and Real Time Hydrological Forecasting Project"; D. H. Newsome, "European Weather Radar: A Tool for UK Water Resources Management," *Journal of the Institution of Water Engineers and Scientists* 40, no. 5 (October 1986): 415–27.

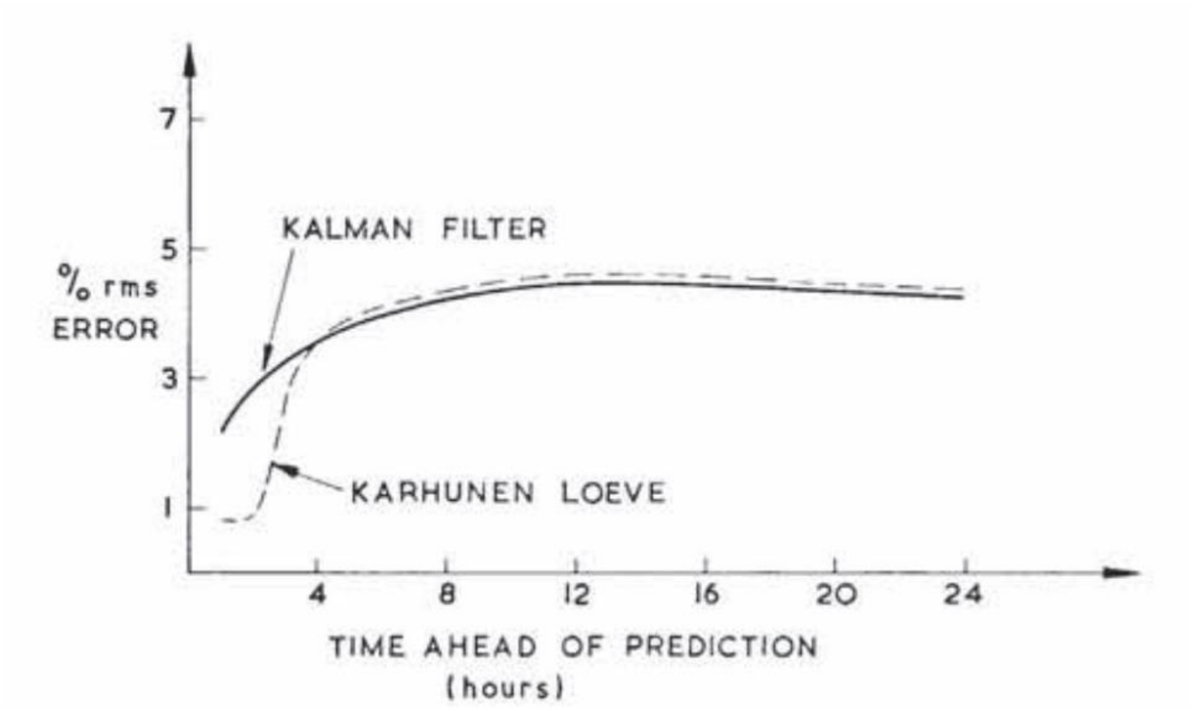

Figure 17. Comparison of errors between Kalman filtering that incorporates atmospheric temperature and a Karhunen-Loeve spectral expansion that used past load data only[47]

The reaction to Marlow and Fallside's 1981 paper was mostly positive, with several commentators highlighting similar systems being developed in their own areas. Specialist water supply companies seemed to be furthest along with developing advanced telecontrol systems, with innovations at the Cambridge Water Company and Bristol Waterworks Company being highlighted.[48] However, representatives of the water authorities also seemed enthusiastic. J. A. Young, the Director of Operations at the Wessex Water Authority, outlined that the authority had developed a "less sophisticated" system for minimising pumping costs.[49] T. A. Harker, a divisional manager for the Severn-Trent Water Authority, heralded the end of the management mantra "When in doubt fill it up and if this does not solve the problem, keep it full", saying that in times of financial stringency a much

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[47] Fallside and Perry, "On-Line Prediction of Consumption for Water Supply Network Control," 404.
[48] Marlow and Fallside, "Minicomputer, Microprocessor and Telecontrol Applications to a Water Supply Network," 538–39.
[49] Marlow and Fallside, 540–41.

more precise method of control was required.[50] F. Earnshaw, the Director of Technical Services at the same authority, exhorted the industry to go further on capital optimization by considering how the whole water distribution system could be redesigned from the ground up to exploit new control techniques.[51]

Even though this interest in optimisation did not lead to increased use of weather information in the case of the water industry, it may have led to increased vulnerability to climatic fluctuations. By the end of the 1980s, in the years leading up to privatisation, the culture within the water industry practice had changed decisively towards a more commercial outlook.[52] As a result, "risk management" became a wider theme of research. The Institution of Water and Environmental Management's symposium *Risk Management in Water and Environmental Services*, held in March 1988, reflected this change. R. Huntington, the Director of Engineering and Operations at the Wessex Water Authority, opened the symposium with a reflection upon how the priorities of the industry were shifting[53]:

> Historically, the water industry in this country has taken a very conservative approach to management of its activities, with heavy emphasis being placed on security and quality of service, rather than on conventional business and commercial objectives. This background, allied to the absence of competition, has resulted in only limited use being made of 'risk management' techniques. However, financial pressures now arising from the use of Performance Aims

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[50] Marlow and Fallside, 541–42.

[51] Marlow and Fallside, 539–40.

[52] One symbol of this change was a whole chapter of The Institution of Water Engineers and Scientists' water services planning manual being dedicated to corporate planning: V. Cocker, "Corporate Planning: Methodology and Processes," in *Water Services Planning*, ed. R. A. Bailey, 1st ed., Water Practice Manuals 6 (31–33 High Holborn, London WC1V 6AX, England: The Institution of Water Engineers and Scientists, 1986), 27–44.

[53] R. Huntington, "The Use of Risk Management to Provide Cost-Effective Water Supplies," *Water and Environment Journal* 2, no. 6 (December 1, 1988): 580.

> and the impending move towards privatisation, is focusing attention on the need to use more analysis in a practical manner to enable a sensible balance to be struck between service and costs.

This change in culture was reflected by new optimisation practices, which pushed at storage margins in reservoirs and contributed to systemic vulnerabilities to atmospheric changes. A group of engineers supported by Thames Water commenting at the same symposium that the "prevailing climate is one in which operational cost savings are being sought, and it is natural to couple operational data with readily-available computing power in the development of control policies which result in cheaper network operation." This group applied such computing power to determining the "minimum permissible storage" in an optimized water distribution network; the change in culture made cutting the margin between supply and demand seem reasonable and desirable.[54]

Often the mathematics involved in risk analysis within the water industry was not particularly complicated.[55] Huntington, who described risk analysis as "rationalizing uncertainty," divided the process into three steps. Firstly, he recommended to break down the uncertainty into components and establish the relationships between these components, in a mathematical form if possible. Secondly, he recommended to identify the required data to make these relationships meaningful. Finally, he asked that data should be collected and manipulated in way to "ensure the issues are clear."[56] As an example, Huntington examined the management of reservoir levels, saying that a logical approach was to quantify three elements; savings, risk and consequences. Interestingly, Huntington claimed that it was "relatively straightforward" to quantify savings and decide the

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[54] R. P. Warren et al., "Optimization of Water Supply Systems: Risk Analysis and Reliability of Supply," *Water and Environment Journal* 3, no. 1 (February 1, 1989): 22.

[55] By Huntington's own admission: Huntington, "The Use of Risk Management to Provide Cost-Effective Water Supplies," 580.

[56] Huntington, 581.

acceptability of consequences, the latter of which suggests that he was not considering many ethical dimensions of what, for example, cutting off a family's water supply for a set amount of time would mean. The real challenge, so Huntington thought, was the quantification of risk, and he does not provide any solid methodologies for doing so, but just lists the factors that should be considered. The product of this, it appears, was an optimised reservoir management system at the Wessex Water Authority where well-defined savings were measured up against risks that were much less well-defined. Huntington lets us know the consequences: "Using this technique facilitated a reduction in storage standard from 24 to 18 hr. Recently, this has been further reduced to 15 hr after gaining confidence in operating the system. These changes have resulted in substantial savings in capital expenditure."[57] It is easy to imagine that senior management could breathe a sigh of relief, knowing that reservoir capacity was more than sufficient after all. Risk analysis became a substitute for system expansion, legitimising decisions that made the system more susceptible to climate events.

The paper by the team from Thames Water provided a more formalised methodology for quantifying risk, drawing on probability analysis published in 1986 by a group at the Imperial College of Science and Technology.[58] The Thames Water project considered a system where pumping costs were optimised by exploiting cheaper electricity tariffs during night-time, increasing reservoir storage during the night and allowing this storage to deplete during the day. The paper aimed to find the minimum level that reservoir levels could fall to while maintaining network reliability. It appears that the methodology would also be used to override the concerns of operators: "[…] having chosen the minimum permissible reservoir storages, there may be a certain reluctance on the part of the system

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[57] Huntington, 582.

[58] G. Germanopoulos, P. W. Jowitt, and J. P. Lumbers, "Assessing the Reliability of Supply and Level of Service for Water Distribution Systems," *Proceedings of the Institution of Civil Engineers* 80, no. 2 (April 1986): 413–28.

operators to lower reservoir levels to their minimum under a heuristic optimization scheme; such reluctance may not be present in a formal optimization.”[59] The paper considered three types of device failure: a failure of a water source or a pressure booster at a pumping station, a critical valve being stuck open or shut, or a burst in a critical area of the network. First, the consequences of worst-case scenarios were considered using simple steady-state models of the network under constant flows and demands. Then, these models were refined by adding in a realistic demand profile (e.g. Fig. 16) and extended period simulations. Finally, the probabilities of such scenarios for a given time were estimated by assuming that the probabilities of failure followed a Poisson distribution and feeding in past failure data. The paper was then able to give minimum storage requirements for different acceptable probabilities of supply failure. The paper gives an example where a 95% probability requirement for no failures in ten years requires 21h of storage, whereas a 95% probability of a single failure in ten years would require only 11h of storage, leading to a substantial saving. Predictably, the paper makes no effort to define what the acceptable level of failure actually was. In addition, this methodology assumed that failures always had the same probability, when poorly maintained systems would clearly fail more frequently as time passed.

Indeed, in addition to optimisation drives that pushed at storage margins, which could save money at relatively little investment, there was a neglect of costly long-term expansions of the system and expensive maintenance investments to control leakage from pipes. Hassan argues that the water industry suffered the most of all public sectors from the cuts of the 1970s and 80s. When the 1979 Thatcher government told the industry to cut its planned investments for the following year by 11.2%, the National Water Council stated that the industry would comply “But the paring down process of the last five years does mean that

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[59] Warren et al., “Optimization of Water Supply Systems,” 22.

the current programmes are "lean" rather than "fat" and therefore cuts will penetrate into the essential tissue of what is needed." This process diminished long-term priorities in the industry, contributing to an infrastructure crisis. In the long run, so Hassan argues, the government was resorting to a course of "asset depletion," leading to the deterioration of the industry's "environmental and physical capital."[60] Funding restrictions and changing management styles also helped deplete the personnel of water distributors, with the staff levels in Yorkshire for example almost halving 1975–95, with the losses also diminishing local expertise within the system.[61] Although it would take until 1995 to manifest fully in public discourse, this process of depletion contributed to a supply security crisis that instigated a new change in direction for the industry, and contributed to new ways that the atmosphere was conceptualised.[62]

Drought, Headroom, and Reregulation

The drought of 1995–6 was one of the most serious failures of UK water supply since the Second World War. For much of the Spring and Summer of 1995, the high-pressure cell that usually resides on the Azores extended northward, bringing subtropical airmasses across the UK. As a result, rainfall figures for June–August 1995 were the driest in over two centuries for England and Wales, marginally more severe than 1976, and the drought represented the third-driest eighteen-month span on record. Some areas, such as West Yorkshire, were particularly affected, with the drought only being declared over and

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[60] Hassan, *A History of Water in Modern England and Wales*, 158–61.

[61] Karen J. Bakker, "Privatizing Water, Producing Scarcity: The Yorkshire Drought of 1995," *Economic Geography* 76, no. 1 (2000): 19.

[62] One of the few whistle-blowers for some of these problems was retired, perhaps suggesting that it was difficult to publicly voice concern from within the industry: P. T. McIntosh, "Water Resources Development: A Balanced Approach," *Water and Environment Journal* 7, no. 4 (August 1, 1993): 412–17. With privatisation in 1989, water companies were able to raise ample capital for investment. However, correcting the depletion of the previous years would take decades, and in the meantime new and tougher regulatory bodies were less likely to grant abstraction licences: Jack Carnell, interview by Robert Luke Naylor, Telephone, June 6, 2022.

restrictions being eased in November 1996.[63] Details of the operational response before, during, and after the drought in Yorkshire were provided by geographer Karen J. Bakker, who undertook 24 formal interviews during and soon after the drought. Interviewees included representatives of regulators, Yorkshire Water Services management, the civil service, and lobby groups.[64]

The winter of 1994–5 was extremely wet, so by the beginning of Spring groundwater levels were well above average and reservoirs were close to full. As a result, and following usual procedure, operators at Yorkshire Water Services began to supply water directly from high-altitude reservoirs, which represented a cheaper method than pumping water from rivers. Of course, this technique also depleted water storage, accentuating the effects of drought. Bakker reports that the Environment Agency had raised concern over this practice the year previously, but that Yorkshire Water had changed its practices little, partly as a result of forecasts that suggested industrial demand would decline and domestic demand would remain steady; “Although there was a fairly narrow margin between supply and demand, it was assumed that there would be no cause for concern until the turn of the century.”[65] The company also made little investment in repairing leakage in the system and increasing headroom, instead paying a £50m special dividend to its parent company, Yorkshire Water plc, in the Summer of 1995. At the height of the drought, it is estimated that losses from leakage was around the same as domestic consumption. To make matters worse, distribution output during the drought rose to unusually high levels, reflecting high levels of demand. Publicity campaigns to conserve water failed, largely due to public perceptions of

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[63] T. J. Marsh and P. S. Turton, “The 1995 Drought—a Water Resources Perspective,” *Weather* 51, no. 2 (February 1996): 46–53; T J Marsh, “The 1995 UK Drought—a Signal of Climatic Instability?,” *Proceedings of the Institution of Civil Engineers—Water, Maritime and Energy* 118, no. 3 (September 1996): 189–95; Terry Marsh, Gwyneth Cole, and Rob Wilby, “Major Droughts in England and Wales, 1800–2006,” *Weather* 62, no. 4 (2007): 87–93.

[64] Bakker, “Privatizing Water, Producing Scarcity”; Karen J. Bakker, *An Uncooperative Commodity: Privatizing Water in England and Wales* (Oxford University Press, 2003), chap. 5.

[65] Bakker, “Privatizing Water, Producing Scarcity,” 10.

company mismanagement and a series of PR missteps, including a £10 refund to all domestic customers due to “efficiency savings since privatisation.”[66]

Reservoir levels fell throughout West Yorkshire, but the largest deficiencies were experienced by smaller reservoirs such as those that supplied the cities of Bradford and Halifax. By August, several reservoir groups had fallen to a quarter of capacity or less. As the system was set up to pump water from the usually wet west to the drier east, there was no way to quickly rectify these deficiencies. The company then imposed a hosepipe ban, and six weeks later than its own guidance dictated, applied for drought orders to allow increased water pumping from rivers beyond the amounts usually licenced. This pumping caused several rivers to fall to record low levels, and the Environment Agency detected changes to river ecology as a result. In September, the company began transferring water from east to west by road. At its height, 700 tanker trucks were involved in this 24-hour operation. Many of these vehicles had to be imported from Scandinavia due to local shortage.[67] Yorkshire Water Services also applied for drought orders to impose rota cuts to supply, although in the end this drastic and politically volatile measure was not used in Yorkshire at least.[68]

The problems of the 1995–6 drought went beyond the borders of Yorkshire, with thousands of households facing a complete loss of supply due to resource difficulties, and meter areas reporting inadequacies in mains capacity, reservoir storage, and pumping capacity.[69] This sent shockwaves through industry, regulators, and government. The conference “Supply and Demand: A Fragile Balance,” held in March 1996 while the drought

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[66] Bakker, 12.

[67] “The Tanker Drought—1995 to 1998,” Historic Droughts, February 13, 2019, accessed September 14, 2022, https://historicdroughts.ceh.ac.uk/content/tanker-drought-1995-1998.

[68] The drought had similar effects in the North West of England: S. Walker and H. A. Smithers, “A Review of the 1995–96 Drought in the North West,” *Water and Environment Journal* 12, no. 4 (August 1, 1998): 273–79.

[69] WRc Plc, “An Assessment of the Supply Problems Experienced in 1995” (London: UK Water Industry Research, 1996), 7, UKWIR Library of Research Outcome Reports.

was still ongoing, allowed senior figures to give their initial reactions.[70] Whilst delegates acknowledged that "the UK had ample resource potential," most attendees focused on demand management, externalising the blame for the crisis towards public reluctance to adhere to requests for reduced consumption. There were also a couple of references to climate change as a possible contributor to the shortage. However, Yorkshire MPs from both Labour and the ruling Conservatives took a different view, pinning the blame for the crisis on Yorkshire Water's management, with Conservative MP Elizabeth Peakock asking during a House of Commons debate: "Does the hon. Lady agree that if Yorkshire Water had had first-class management last year, we would not have had a crisis because there was not a drought?"[71] This was in reference to the fact that East Yorkshire had abundant supplies, even as West Yorkshire was dry. To these MPs, the events of 1995 were very much a product of company mismanagement.

In response to these competing narratives, two government departments published a call for action that advocated for both demand-management and the possible development of new water resources, with ample mention of other (perhaps less controversial) pressures such a climate change.[72] Bakker argues that the 1995 drought contributed strongly to a change in the regulatory regime of the water industry. In the early 1990s, the development of water resources was a low priority for the Office of Water Services, then the primary industry regulator. For example, planning with headroom was not mentioned in the Office of Water Services' 1994 periodic review. Instead, the focus was on meeting European Union water quality directives. After the drought, government, industry and regulators re-examined the management of water resources, leading to both headroom and climate

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[70] Richard Bailey, "Proceedings of Conference on 'Supply and Demand: A Fragile Balance,'" *Water and Environment Journal* 10, no. 4 (August 1, 1996): 297–300.
[71] "HC Debate 01 April 1996," in *Hansard*, vol. 275 (House of Lords Hansard and the House of Lords Library, 1996), Col. 128.
[72] Department of the Environment and Welsh Office, *Water Resources and Supply: Agenda for Action* (London: The Stationery Office, 1996).

change being included in the Office of Water Services' 1997 periodic review for the first time. At a summit held in May 1997, the government called on regulators to lead in drought planning and management, in effect largely pushing market forces out of the process. The summit led to mandatory leakage reduction targets and new statutory duties to promote water conservation.[73]

However, the industry itself had already been pushing for increased abstraction from regulators, reacting to the capacity crisis before it manifested in 1995. Prior to privatisation, the industry had enjoyed an extremely close relationship with the National Rivers Authorities that granted licences for water abstraction, even sharing office space, meaning that requests were rarely refused. However, with privatisation, regulators became more resistant, requiring water companies to come up with numerical analysis to back up their requests.[74] This led to new research projects initiated by the industry into the calculation of an easily auditable headroom.[75] The government then used these newly developed methodologies as part of its regulatory requirements. In 2004, ministers issued principle guidance requiring water companies "to plan to have sufficient headroom and use appropriate methodologies and guidance to achieve this,"[76] and at least at the time of writing, water companies release five-yearly reports under statutory requirement that

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[73] Bakker, "Privatizing Water, Producing Scarcity," 18; Bakker, *An Uncooperative Commodity*, 119.

[74] Carnell, interview.

[75] Jack Carnell et al., "Water Supply and Demand Balances: Converting Uncertainty Into Headroom," *Water and Environment Journal* 13, no. 6 (December 1, 1999): 413–19; Paul Chadwick and Diane Thomas, "An Improved Methodology for Assessing Headroom" (London: UK Water Industry Research, 2002), UKWIR Library of Research Outcome Reports. The interviews outlined by Carnell et al. suggest that headroom was often an afterthought prior to standardisation and resultant auditability. The estimated headroom reported of 5–10% of water available for use should perhaps be taken with a grain of salt considering that in the same set of interviews the Environment Agency emphasised the need to avoid double-counting.

[76] United Utilities Water Limited, "Target Headroom," Technical Report, Final Water Resources Management Plan 2019 (Warrington, UK: United Utilities Water Limited, 2019), 3.

include discussions of headroom within their distribution systems and the methodologies used to calculate it.[77]

From 1998 headroom calculations have included numerical estimates of the effects of climate change, representing a new turn in how the industry viewed the atmosphere for supply purposes. The first study to synthesise a nationally standardised method of "converting uncertainty into headroom" was undertaken by Jack Carnell, Director of the South Staffordshire Water Company, supported by a group from the engineering consultancy Halcrow. Carnell joined the South Staffordshire Water Company in 1974 as a trainee draftsman and worked his way up. Clearly ambitious, he gained an unusually large number of qualifications as he rose (e.g. BSc in Civil Engineering, MSc in Mathematics, PMD in management).[78] He had previously, as part of his role at the company's planning unit in 1986, done work investigating the use of atmospheric information in the optimisation of the water supply system.[79] Now in 1998 his work would inform headroom calculations that in many cases would lead to de-optimisation for the sake of system security.

The project was supported by UK Water Industry Research Ltd, a joint research collaborative of water companies.[80] Carnell et al.'s methodology was used across the industry during the 1998 supply/demand balance submissions to regulators, and basically provided a methodology for deciding what percentage of water available for use should become target headroom, defined as "the minimum buffer that a prudent water company should allow between supply […] and demand to cater for specified uncertainties in supply

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[77] E.g. United Utilities Water Limited, "Target Headroom"; R MacDonald and S Pike, "Company Headroom Analysis," Water Resource Management Plan 2019 (South Staffs Water, October 31, 2018); Severn Trent Water, "Appendix C: Dealing with Uncertainty," Water Resource Management Plan 2014 (Severn Trent Water, 2014).

[78] "6 Degrees of Aston," *Aston In Touch*, 2019.

[79] Carnell, "Short Term Demand Forecasting."

[80] Founded in 1993, the board of UK Water Industry Research Ltd are directors or senior managers of member companies. All of the Water Companies in the UK and Ireland are members.

and demand […].”[81] The methodology was similar to that applied in risk analysis during the 1980s. Drawing on two industry-wide seminars, the major potential uncertainties and their characteristics were listed. Then, based on “judgement and empirical evidence,”[82] each uncertainty factor was given a score to indicate the weight of its contribution to headroom (Fig. 18). Climate change was assessed to have at most a “medium” effect on headroom through its impact on supply and a “low” effect on headroom through its impact on demand. These factors were then combined to give a total headroom value that for most resource zones lay between 6% to 8% of the water available for use.

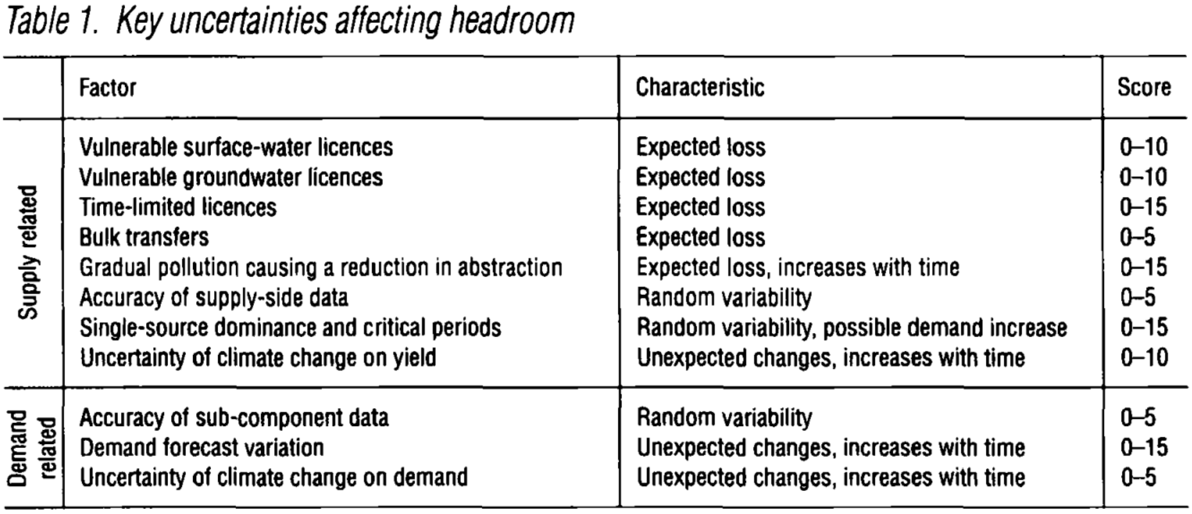

Table 1. Key uncertainties affecting headroom

	Factor	Characteristic	Score
Supply related	Vulnerable surface-water licences	Expected loss	0–10
	Vulnerable groundwater licences	Expected loss	0–10
	Time-limited licences	Expected loss	0–15
	Bulk transfers	Expected loss	0–5
	Gradual pollution causing a reduction in abstraction	Expected loss, increases with time	0–15
	Accuracy of supply-side data	Random variability	0–5
	Single-source dominance and critical periods	Random variability, possible demand increase	0–15
	Uncertainty of climate change on yield	Unexpected changes, increases with time	0–10
Demand related	Accuracy of sub-component data	Random variability	0–5
	Demand forecast variation	Unexpected changes, increases with time	0–15
	Uncertainty of climate change on demand	Unexpected changes, increases with time	0–5

Figure 18. List of uncertainties affecting headroom agreed upon at two industry-wide seminars shortly after the 1995 drought[83]

Although Carnell’s methodology was used for regulatory submissions in 1998, many problems with the technique were reported. Many of the issues regarded the fact that the scoring system averaged out risks, meaning that the effects of extremes were suppressed.

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[81] Carnell et al., “Water Supply and Demand Balances,” 415.

[82] Carnell et al., 416.

[83] Carnell et al., 416. According to Carnell, the effects of climate change were estimated through a series of surrogates, some of which increased demand (e.g. increased garden watering) and some of which decreased demand/supply (e.g. move to low-flush systems, move away from baths to showers, decrease in groundwater): Carnell, interview.

In addition, the result was not expressed in probabilistic terms, meaning that could not easily be combined with other aspects of the supply-demand balance. As a result, around the turn of the millennium UK Water Industry Research Ltd commissioned research into a new probabilistic model undertaken by a group from Mott Macdonald Ltd, a multidisciplinary consultancy.[84] The uncertainties of each component (there was only one addition from Fig. 18) were defined as probability distributions and combined using repeated random sampling. Climate impacts were recommended to be defined through the UK Climate Impacts Programme that published a standard set of climate scenarios to be used in research.[85] Through these calculations of headroom, we see many of the same judgement-based and probabilistic techniques as used for risk analysis in the industry in the 1980s. However, instead of these techniques being used to squeeze margins under commercial pressure, we see these same methods often used to expand and define margins under regulatory pressure. With this shift, we see conceptualisations of the changing atmosphere shifting away from a potential source for hour-by-hour optimisation towards a factor that needed to be incorporated into long-term planning.

Changes in Economic Climate—Changes in Perceptions of Climate

With the gas industry we witnessed a profound infrastructural shift in the 1970s as a result of the discovery and exploitation of North Sea gas, leading to a system that was much more reliant on atmospheric forecasting. With water, the shift mainly took place in the 1980s, as a civic ethos gave way to commercial concerns regarding efficiency and cost-savings as a result of government directives and budget cuts. As this occurred, we see a temporary shift away from more interest in long-term “static” climate information towards more interest in

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[84] Chadwick and Thomas, “An Improved Methodology for Assessing Headroom.”

[85] For more on the UK Climate Impacts Programme: Merylyn McKenzie Hedger, Richenda Connell, and Penny Bramwell, “Bridging the Gap: Empowering Decision-Making for Adaptation through the UK Climate Impacts Programme,” *Climate Policy* 6, no. 2 (January 2006): 201–15.

short-term weather changes for operational purposes, as well as an increased development and usage of optimisation techniques that clinched at the margin between supply and demand. In addition, we see (in retrospect) a government-induced underinvestment in the maintenance and development of water infrastructure, and the introduction of risk analysis techniques to justify squeezing as much utility as possible from existing infrastructure. In 1995, during a severe drought, the water supply system failed for thousands of households. Systemic problems such as long-term underinvestment in leakage repairs, pointed out by industry figures more than a decade before,[86] contributed to this failure. Nevertheless, the event quickly became associated with climate change, which formed a component of headroom calculations that constituted part of the response.

As time passes, we see changes to both conceptualisations of the atmosphere and vulnerabilities to atmospheric fluctuations, not necessarily as a result of climate change, but as a result of "economic climate change." Prior to the 1980s, for operational purposes rainfall was seen as a static resource to an extent that alarmed Herbert Lapworth as he spoke in 1930. Managers were more than happy to receive rain gauge information on no more than a monthly basis, and long-term rainfall statistics were prized for their ability to give an insight into the "true" climate. As budgets were tightened and staff-levels were cut, atmospheric knowledge became a potential cost-saving mechanism. Although never acted upon in practice, in conceptual terms the temporal scale of the atmosphere became restricted—the importance of knowing what the atmosphere was doing in the next hour became of greater interest than what the atmosphere was doing for the next decade. Finally, when the industry came under the cosh of new regulatory powers, industry

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[86] It should be noted that similar noises have recently been made by the water industry as a result of a lower than expected determinations by the Office of Water Services. Climate change features heavily in these arguments: Jillian Ambrose, "Yorkshire Water Challenges Regulator over Price Controls," *The Guardian*, February 10, 2020, sec. Business; "Response to the CMA's Findings in Relation to Ofwat's PR19 Final Determination," Anglian Water Services, March 17, 2021.

planners were centrally directed to consider a changing climate as part of their long-term planning. As our distributions systems change, so does climate.

Conclusion—How the Atmospheric Resource is Made

Throughout this thesis, we have seen the use of formal atmospheric information emerge in UK utilities systems. In all three industries, we first see formal atmospheric information be incorporated as a *diagnostic tool*, albeit beginning at very different times depending on the industry in question. In the case of water, we see long-term rainfall statistics used to measure the efficiency of existing infrastructure since the nineteenth century, a mode of practice that continued into the post-war period. In the case of gas, we see interwar engineers use the concept of the degree day to measure the efficiency of heating in buildings, as well as the “loss” of product as a result of pressure changes. In the case of electricity (and gas to a more limited extent) during and immediately after the Second World War, we see engineers use climate information used in an attempt to isolate and analyse changes in demand that were not weather dependent, in an attempt to highlight the problems of an increasing peak demand. In all of these cases, atmospheric information was not being used to directly operate or construct the system, but to examine and highlight systematic flaws. Hence, the atmosphere was a diagnostic tool.

Then, we see the atmosphere develop as an *optimisation tool*, as changes to the economic environment led engineers to develop models to increase efficiency. We first encounter this in the electricity and gas industries during the 1940s and 50s, when war-induced shortage forced engineers to focus on efficiency in order to save precious coal. In the latter half of the 1960s, the gas industry showed a renewed interest in using weather information for system optimisation, as the exploitation of North Sea gas gave rise to a system that was much more dependent on weather-based demand forecasting. In the 1970s and 80s, under the pressure of cuts in government funding, managers within the UK water industry developed models that used weather information to minimise pumping costs, although in the case of the water industry weather-based optimisation models appear to have never been used in practice during the time in question. Weather-based models were used in the gas and electricity industries in operational procedure to reduce waste and conserve energy by clinching at the material and temporal gap between supply and demand. In these cases, the atmosphere performed as an optimisation tool.

Finally, we see the atmosphere become a *planning tool*. We see this tool emerge in the electricity industry circa 1960, when the UK government became more interested in using indicative planning to achieve full employment. Economic planning had to be underpinned by planned expansion of the electricity supply industry, and investigations into climatological data provided a benchmark through which planning margins could be set. In the case of the gas industry, interest in climate records long-term climate records mainly coincided with the planning and construction of the National Transmission System, where the minimum required storage capacity had to be calculated. In the water industry, although rainfall records had long informed system expansion, the atmosphere found renewed relevance when climate change was incorporated into long-term planning under the pressure of an emboldened regulator. In these cases, atmospheric information informed the planned construction of the electricity, gas, and water distribution systems. The atmosphere became a planning tool.

This thesis has suggested how climate and weather themselves, to an extent, were *constructed* or *emergent* within the electricity, gas, and water distribution systems. Following broader trends in the literature, it could be said that the weather and climate that emerged in the UK utilities were not the same as the weather and climate of meteorological institutions. The weather within the gas and electricity industries was reconstructed as an entity with simplified relationships to consumption, with variables such as effective temperature, daylight illumination, cooling power of the wind, and rate of precipitation replacing meteorological variables such as temperature, windspeed, cloud coverage, visibility, precipitation, and pressure. These industries were often working against the way that atmospheric information was processed, produced, and provided by the Meteorological Office—in this history it is the provider of weather information that remains largely passive. The weather of the utilities industries is also *national* or *regional*; the mathematical definition of variables that corresponded to consumption depended on the cultural energy-dependent responses of the system users, as well as the regulatory effects of legislation on industry. Effective temperature in the United States, where air conditioning is a culturally and technologically embedded response to warm weather, is different to a British effective temperature.

In all three of the industries examined in this thesis, climate was constructed as a stable planning variable. More precisely, it was based on static probability curves that allowed industries to specify acceptable chances of failure. This was done despite some level of awareness in all three industries of the debates within climatology about long-term shifts in climate. This resonates with the thesis of Mike Hulme that climate operates as a cultural stabilizer in order accommodate an ever-changing atmosphere—the *useful* climate, both cultural and technological, appears to have been stable.[1] The exception to this static rule is the water industry of the late 1990s, which began to explicitly incorporate a changing climate into long-term planning. Perhaps this was a reflection of the framing of climate change as global *warming*, a phenomenon that has become associated with drought in the popular imagination, with drought having a much greater effect on the water industry than electricity or gas. More work would be required to substantiate this idea.

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[1] Hulme, *Weathered*.

Throughout this thesis, we have seen different drivers for interest in the atmosphere between those who actually operated large technological systems and politicians who were more widely perceived as responsible when systems failed. Politicians were much more likely to respond directly to system failures induced by harsh atmospheric conditions, pressuring industry to change practice with regard to the use of atmospheric information. This can be seen in the response to the 1962–3 winter and the 1995 drought. However, in both of these cases, changes were already being made within industry by the time the adverse atmospheric conditions hit, usually in response to longer-term weaknesses induced by changes to the national economy that harsh atmospheric conditions simply highlighted. In addition, as may well be expected, politicians monolithised systems and industries that they did not understand, as was seen when the Ministry of Power unsuccessfully pressured the gas and electricity industries to use a common system for processing weather forecasts based on British computers. Nevertheless, politicians did have an *indirect* and *unintentional* impact on how atmospheric information was used within the UK utilities through policy frameworks. For example, policies that reduced available resources for public utilities led to weather-based optimisation and policies that encouraged long-term econometric planning led to investigations into climatological data.

This thesis has shown a transfer of power within the UK utilities from local dispatchers to centralised controllers, which was reflected by an increased use of formalised weather information. We have seen it repeatedly stated that local dispatchers had an intuitive feel for how their designated area would respond to weather conditions based on experience and rules of thumb. It can also be assumed, due to the fact that these local dispatchers lived in the area they served, that these dispatchers were able to use their own bodily senses to bypass the formal mathematical relationships that were later required by central controllers—they were able to vary the supply according to whether they themselves felt cold, for example. In the third and fourth chapters, we also see hints of tension between management and shift engineers, with management being more interested in increasing efficiency and shift engineers being more interested in avoiding catastrophic failure. These tensions came at a time of increased industrial strife more generally between shift staff and management. It is worth asking the question of whether centralised controllers became alienated from the people and areas that they served, and whether this contributed to a greater interest in efficiency rather than security of supply. These questions could form the basis of further work.

We have also seen a contrast between how those within meteorological institutions advertised weather services and how those within the utilities industry valued the weather. In only one case in this thesis do we see a numerical financial value (admittedly an impressive sum of £50m) placed upon the forecasts that atmospheric information informed. Rather, we see the value of weather become an implicit assumption between those who had a deep knowledge of how the utilities systems worked. Indeed, often the monetary value was impossible to measure, as was the case when a minority of power engineers used atmospheric information to argue against electricity system expansion, a trajectory that would hit bottom lines negatively at least in the short term. The value of weather was impossible to ascertain until a deep knowledge of the system was applied. System managers were unlikely to be impressed by the back of the napkin monetary calculations produced by meteorological institutions shown in chapter one.

Optimisation

The fact that consumers can economically order products to their doors within twenty-four hours is a wonder of the modern world, but for many of the world’s corporations twenty-four hours is still too long. The news rebounds with the latest innovations by Amazon, eliminating the slow human being from the supply chain. Vans are replaced by drones,[2] workers are replaced by warehouse robots,[3] and brains are replaced by artificial intelligence.[4] Amazon warehouses increasingly defy the image of a warehouse as a place of storage—an ever-larger percentage of warehouse activity is dynamic. Optimisation, under names such as just in time (J-I-T) production, feeds off the temporal and material gap between supply and demand, eliminating redundancies and their associated costs. However, as this thesis shows and other weather scholars have claimed, it does so at considerable risk.[5]

The Achilles' heel of optimisation is that supply systems do not exist in laboratory conditions. Rather, they operate under complex externalities that are outside the control of system managers, the nature of which are fundamentally and sometimes increasingly unknown. There are two non-mutually exclusive ways to secure a supply system against externalities. Firstly, supply and storage margins can be increased in a process of de-optimisation, as we saw happen in parts of the water industry after the drought of 1995.[6] This is unattractive to supply authorities for the same reasons that optimisation is attractive—in ordinary times, optimisation decreases costs and increases speed of service, thereby increasing market share and profit/savings margins. Instead, supply authorities invested in solutions that attempt to both eliminate the threat of externalities and accelerate the process of optimisation. As an alternative to bearing the costs of de-

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[2] Dane Bamburry, "Drones: Designed for Product Delivery," *Design Management Review* 26, no. 1 (2015): 40–48.

[3] Jun-tao Li and Hong-jian Liu, "Design Optimization of Amazon Robotics," *Automation, Control and Intelligent Systems* 4, no. 2 (May 30, 2016): 48–52.

[4] Rupa Dash et al., "Application of Artificial Intelligence in Automation of Supply Chain Management," *Journal of Strategic Innovation and Sustainability* 14, no. 3 (2019): 43–53.

[5] As said by Maureen Agnew and John Thornes "A consequence of the J-I-T development is the heightened sensitivity of food transport to weather extremes": Maureen D Agnew and John E. Thornes, "The Weather Sensitivity of the UK Food Retail and Distribution Industry," *Meteorological Applications* 2, no. 2 (1995): 137–47.

[6] Carnell et al., "Water Supply and Demand Balances"; Chadwick and Thomas, "An Improved Methodology for Assessing Headroom."

optimisation, supply authorities have invested in forecasts and models that aim to predict externalities and metamorphose them into an integral component of their supply system. Thus, rather than optimising a supply system under the threat of externalities, supply authorities optimise an integrated externality-supply system.[7] Short-term fluctuations in the atmosphere—weather—represents a good candidate for integration. Weather can be forecast with a level of certainty and has an influence on supply and demand in many supply systems. Few people buy sunscreen or ice cream when the weather is overcast,[8] few roads need to be de-iced when the temperature is warm,[9] and little electricity can be generated when a wind turbine is becalmed.[10] As a result, as shown in this thesis, supply authorities have incorporated weather into their systems, eventually on a systematic basis. Weather has come to be seen as a controlled variable—similar to personnel or material.

However, there are limits to the extent that atmospheric changes can be incorporated into supply systems. Not only does the weather need to be forecast, but so does the effect of the weather upon ever-changing supply systems. Weather-sensitive wind power is becoming an ever-larger part of the UK's energy mix, and the idea that a gust of wind could halt ten percent of world trade was implausible until the Suez Canal was built and container ships became large enough to block it.[11] In addition, the behaviour of the externalities are difficult to predict and are often changing themselves. Unlike the weather, longer term atmospheric changes cannot be forecast with anywhere near the same level of certainty.

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[7] For more on the (often artificial) separation between systems and environment: Thomas P Hughes, "The Evolution of Large Technological Systems," in *The Social Construction of Technological Systems. New Directions in the Sociology and History of Technology*, ed. W. E. Bijker, T. P. Hughes, and T. Pinch (Cambridge, Massachusetts & London, England: MIT Press, 1987), 51–82.

[8] Agnew and Thornes, "The Weather Sensitivity of the UK Food Retail and Distribution Industry."

[9] John E. Thornes, "The Prediction of Ice Formation on Motorways in Britain" (PhD, London, University College London, 1984).

[10] Edward William Golding and R. I. Harris, *The Generation of Electricity by Wind Power* (E. & F. N. Spon, 1976).

[11] "The Cost of the Suez Canal Blockage," *BBC News*, March 29, 2021, sec. Business; A. O. Lebedev, M. P. Lebedeva, and A. A. Butsanets, "Could the Accident of 'Ever Given' Have Been Avoided in the Suez Canal?," *Journal of Physics: Conference Series* 2061, no. 1 (October 2021).

Respectable climate scientists cannot say whether next winter will be severe or mild, and the complex effects of climate change add even more uncertainty to the mix. This is when the optimisation of supply systems and the complexities of the atmosphere come into conflict. Under these circumstances, the atmosphere is reframed under the designation of risk. The system is consciously allowed to fail a certain percentage of the time, as long as the consequences do not place the bottom line in jeopardy.[12] As this thesis has shown, industries have carefully analysed long-term climate information in order to inform the range of seasonal conditions that risk-based models should be preparing for. In the case of electricity, these models continue to frame climate as a long-term average of weather conditions, even as climate change becomes an ever-larger feature of public discourse.[13]

However, within policy circles, change is in the air with regard to how supply systems should be managed, with more focus apparently being directed towards security rather than optimisation. Renewed geopolitical conflict has caused European nations, including the UK, to reassess energy policy, ostensibly focusing more on energy independence and security than engagement with global markets.[14] However, this change in attitude has yet to filter into attitudes towards the atmosphere. Weather-dependent renewable energy is becoming an ever-larger component of the UK's energy mix, and there is a volumous literature exploring how the development of renewable energy has resulted in greater

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[12] Interestingly, this was often the case regardless of the ownership model of the utilities in post-war Britain. As an example, nationalised gas and electricity boards, with their roots in private enterprise, kept the same personnel and attitudes as they transitioned into public ownership in the late 1940s. Competition with each other was a prime driver of initiatives in the immediate post-war period, as industry specialists fought to keep their jobs secure and ambitious managers sought to impress: Hutchison, *High Speed Gas*. As was acknowledged at the time, parliamentary oversight of the nationalised utilities was often minimal, and the nationalised boards were often expected (in theory) to be financially self-sufficient, with government departments largely only intervening on large capital investments and pricing: David Coombes, *State Enterprise: Business or Politics?* (London: Allen & Unwin, 1971).

[13] Richards and Ong, "Average Cold Spell (ACS) Methodology."

[14] Department for Business, Energy, and Industrial Strategy and Prime Minister's Office, 10 Downing Street, "British Energy Security Strategy," Government, GOV.UK, April 7, 2022, https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy.

weather sensitivity of energy systems.[15] However, there is evidence that this variable electricity source has not been adequately prepared for by successive UK governments over the past two decades. The usual method for accounting for windless days is gas-powered generation that can be quickly activated and deactivated. The affordability of such generation depends on gas storage to smooth out variations in international gas prices, which governments during the 2000s and 2010s decided to leave to the market, believing that cushioning exploitable price rises would disincentivise private investment. As said by Jonathan Stern, a distinguished research fellow at the Oxford Institute of Energy Studies in 2021: “All governments rejected the chance to do something about this during the 2000s, early 2010s, when there were lots of storage projects that needed funding. They decided to ‘leave it to the market.’ Last year that was a great decision with huge supply, low demand, and record-low prices; this year, not so good.”[16] More serious supply shortages in the last twenty years may only have been avoided due to economic slowdown and relatively mild winters.

This thesis has shown how a focus on energy security will also require a rethink of how the atmosphere is used within the industries in question. Long-term climate information has traditionally been used to minimise investment in critical infrastructure, as most clearly demonstrated in the gas chapter of this thesis. However, as suggested by the water chapter of this work, atmospheric information can also be used to justify new supply buffers in order to increase security. At a time when the UK energy supply mix is becoming increasingly sensitive to an increasingly unpredictable atmosphere, buffers in the UK

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[15] Laura C. Dawkins, “Weather and Climate Related Sensitivities and Risks in a Highly Renewable UK Energy System: A Literature Review” (Meteorological Office, June 24, 2019). When the author visited the National Grid headquarters in early 2020 staff demonstrated the latest forecasting systems for predicting the electricity production of offshore windfarms.

[16] Isis Almeida, “U.K.’s Lack of Gas Plan Leaves Country at Mercy of Global Market,” *Financial Post*, September 21, 2021, sec. FP Energy.

energy supply, such as demand management techniques (e.g. insulation) and storage, seem an increasingly worthy public investment.

What Sort of Atmospheric Information is Needed to Promote Better Decision-Making?

This thesis has shown how the atmospheric information required by large technological systems is intimately linked, in terms of spatial and temporal requirements, to how those systems are constructed and operated. For example, atmospheric information regarding the peak hour of 5pm was of crucial importance to the electricity industry, a fact that was overlooked by the Meteorological Office in the interwar period.[17] One surprising aspect of the information demanded by the electricity and gas industries was the relative paucity of the spatial locations required for data collection points in order to gain a national picture for operational purposes, a phenomenon that largely resulted from the concentration of the British population in a few large metropolitan areas. As an example, Maurice Davies claimed that only forty-two weather stations nationwide were sufficient in practice for calculating weather-demand relationships in 1958.[18] Although both industries now use weather products that provide a much more continuous picture of the atmosphere across the country, this initial spatial paucity demonstrates how "better data" provided by climate services may very inefficiently serve the needs of users. As new industries arise such as those associated with information technology, new specific requirements for atmospheric information will emerge that the current mode of climate services is ill-equipped to satisfy.[19]

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[17] Select Committee on Nationalised Industries, *The Electricity Supply Industry*, 3:299.

[18] Davies, "The Relationship between Weather and Electricity Demand," 27.

[19] E.g. Juan Camilo Cardona, Rade Stanojevic, and Rubén Cuevas, "On Weather and Internet Traffic Demand," in *Passive and Active Measurement*, ed. Matthew Roughan and Rocky Chang, Lecture Notes in Computer Science (Berlin, Heidelberg: Springer, 2013), 260–63.

Today, how atmospheric information to be used has increasingly become the concern of information providers, rather than end-users as was mostly the case in this thesis. This is partly driven by an increasingly commercialised atmospheric services sector, as well as the privatisation and consequent slimming down of research groups within user-industries.[20] This has led to information providers making broad assumptions about user needs, a problem is recognised by those within climate services, with a survey reporting that providers lack the right incentives, resources, and relationships to make meaningful user-engagement a reality.[21] Information providers are especially ineffectual when it comes to providing services to poorer communities under the current model of commercialised climate services.[22]

So, what is to be done? Firstly, climate services that are provided based on broad assumptions regarding demand are clearly not suited for purpose. This thesis has shown how assumptions made regarding demand cannot even be applied across the utilities, and also cannot be applied within single industries during times of transition, whether that transition be caused by de-industrialisation or the advent of natural gas. Providers of climate services need to understand that the usefulness of their data is contingent upon technological systems that are always changing, sometimes quite rapidly. Secondly, despite the repeated attempts outlined in the introduction, the value of atmospheric information cannot be reduced down to simple monetary valuation, and the processes of data evaluation within climate services, rather than just the outputs of their marketing departments, should reflect this. Going beyond monetary valuation cannot be achieved with a private sector-led approach—now that climate change is a central policy issue,

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[20] Peter Rodgers, "British Gas Set to Cut More than 250 Jobs in Research," *The Independent*, May 2, 1996, sec. Industry View. The Central Electricity Research Laboratory closed in 1992: Ian Morford, "John Samuel Forrest," *Quarterly Journal of the Royal Meteorological Society* 120, no. 517 (1994): 751–52.

[21] Findlater et al., "Climate Services Promise Better Decisions but Mainly Focus on Better Data."

[22] Webber and Donner, "Climate Service Warnings."

governments should not regard climate services as a neutral source of information for policymakers but should take an active role in developing services that suit specific societal needs in the face of climate change. Finally, the production of atmospheric information needs to involve a broader range of actors, including those from the social sciences and the humanities, in order to understand the full scope of the interaction between technological and climate systems.

Historians, as well as humanities scholars in general, are often marginal in current debates regarding climate change vulnerability, both in policy and in wider public discourse.[23] This has been a source of frustration for at least half-a-century. Professor of Political Science Michael Lofchie complained in 1975 how social scientists had been pushed to the margins of discussions of the causes of African hunger, saying that such discourses were left almost completely to "climatologists, physical geographers, water experts, and agronomists."[24] Since the beginning of substantial climate discourse in the 1970s, some climatologists have also complained of disciplinary tightening, claiming that a focus on hydrodynamical simulations of the atmosphere has led to more holistic research methods being neglected.[25] Climate change is a process that takes place at the interface of two highly complex interacting systems. On the one hand is the atmospheric system, which is very difficult to forecast on timescales of more than a couple of weeks, and is very difficult to control (even if such control is advisable, which is far from given). On the other are human systems, such as the large technological systems considered in this thesis. As per the name, climate change is a process that manifests in how the interaction between these complex

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[23] Mike Hulme, "Meet the Humanities," *Nature Climate Change* 1, no. 4 (July 2011): 177–79. Note the lack of engagement with the historical literature in, for example: Greta Thunberg, *The Climate Book*, 1st edition (London: Allen Lane, 2022).

[24] Michael F. Lofchie, "Political and Economic Origins of African Hunger," *The Journal of Modern African Studies* 13, no. 4 (1975): 551.

[25] Janet Martin-Nielsen, "Ways of Knowing Climate: Hubert H. Lamb and Climate Research in the UK," *WIREs Climate Change* 6, no. 5 (2015): 465–77; Robert Luke Naylor, "Reid Bryson: The Crisis Climatologist," *WIREs Climate Change* 13, no. 1 (2022): e744.

systems *changes* over time, usually over substantial timescales. As academics that specialise in how human systems change over substantial periods of time, historians should be playing a much more central role in climate change policy debate. Truly useful atmospheric information can only be operationalised through the participation of the full range of relevant practitioners.

Building a Better Atmosphere—How should the Atmospheric Resource be Managed?

It is widely understood that it is extremely difficult to pinpoint whether increasing damages due to atmospheric fluctuations can be attributed more to atmospheric changes or more to societal changes.[26] However, largely as a result of the framework of the Intergovernmental Panel on Climate Change, climate change is often conceptualised as a scientific issue that acts *upon* society. As opposed to earlier discussions of climate change in the 1970s that often focused on food supply systems,[27] today climate change is associated in the popular imagination with extreme weather events that are perceived as existential threats.[28] This thesis has added to voices arguing that it might be wiser to consider climate change a developmental problem.[29] Climate does not emerge as a problem because of lack of scientific knowledge regarding the climate system, or indeed just because of a single line on

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[26] J. B. Smith et al., "Vulnerability to Climate Change and Reasons for Concern: A Synthesis," in *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, 1st ed. (Cambridge: Cambridge University Press, 2001), 913–67; Roger A. Pielke Jr, *The Rightful Place of Science: Disasters & Climate Change*, 2nd edition (Consortium for Science, Policy & Outcomes, 2018).

[27] Robert Luke Naylor, "The Bryson Synthesis: The Forging of Climatic Change Narratives during the World Food Crisis," *Science in Context* 34, no. 3 (September 2021): 375–91; Walter Orr Roberts, "Climate Change and Its Effect on World Food," *Science and Public Policy* 2, no. 6 (June 1975): 264–66.

[28] Vladimir Janković and David M. Schultz, "Atmosfear: Communicating the Effects of Climate Change on Extreme Weather," *Weather, Climate, and Society* 9, no. 1 (January 1, 2017): 27–37.

[29] Martin Parry, "Climate Change Is a Development Issue, and Only Sustainable Development Can Confront the Challenge," *Climate and Development* 1, no. 1 (March 2009): 5–9.

a graph of carbon dioxide emissions, but because of complex interactions between the changing atmosphere and ever-changing human systems.

As a result, this thesis joins others in questioning the argument made by some within meteorological institutions that the provision of greater quantities of higher-quality weather and climate information will help make systems more resilient to climate change. In his seminal 1981 textbook, British climatologist Hubert Lamb suggested why the industrialised world might be particularly vulnerable to climatic changes[30]:

> We shall see that, contrary to the thinking of a generation ago, mankind is by no means emancipated by science and the technological revolution from the effects of climatic changes and fluctuations. […] The national and international organization of our present civilization with its advanced technology undoubtedly enables us, as never before, to rush help and supplies to relief of the immediate distress caused by natural disasters. It may be doubted, however, whether this complex world-wide community, with its interlocking arrangements and finely adjusted balances, is any more able than its predecessors to absorb the effects of long-term shifts of climate

Although Lamb was talking more in the context of world food production, his words can be applied to the supply systems examined in this thesis.[31] A contradiction has developed in the use of atmospheric information within complex supply systems such as those found in the UK utilities. As shown by this thesis, atmospheric

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[30] Hubert H. Lamb, *Climate, History and the Modern World* (Methuen, 1982), 7. Thanks to Richard Staley for highlighting this quote.

[31] Lamb was an important contributor to climate narratives following the World Food Crisis of the early 1970s: Robert Luke Naylor and Eleanor Shaw, “The 200-Year Cycle: An Early Climate-Based Reaction to the Crisis in the Sahel and Its Uptake in 1973,” *History of Meteorology* 11, no. 1 (2022): 1–17. Interestingly, Lamb was funded in the early 1970s by the electricity board, and he made an appearance in the Journal of the Institution of Water Engineers in 1964: Piper, “Lamb’s Unit to the Slaughter?”; Hubert H. Lamb, “The Weather: Past and Future,” *Journal of the Institution of Water Engineers* 18, no. 1 (February 1964): 69–72.

information has often been used to make supply systems leaner, reducing redundancy and contributing to Lamb’s “interlocking arrangements and finely adjusted balances.” At the same time, we are told by many of those who advocate for the meteorological applications industry that a greater quantity of higher quality atmospheric information can emancipate people from the effects of climate change. Could it be that those who profit from the use of meteorological information are (unknowingly or not) overall contributing to the problem that they purport to solve? Does this fit into a wider pattern where climate change has undertaken an ontological shift to become a market transition, where oil producers and car manufacturers can put climate change in their advertising?[32]

It is true that the atmosphere to a large extent has become hidden in modern life, with many people spending most of their time in climate-controlled environments indoors.[33] However, rather than becoming peripheral as a result, the outside atmosphere has become an ever more essential feature of technological systems that underpin modern ways of living, including indoor climates. Atmosphere-supply studies operate as an infrastructural activity, fundamentally invisible in everyday life until they fail, even though they play an ever more important role in determining who gets light, heat, and water and when in a changing atmosphere and economy.[34] Perhaps it is time to bring atmosphere-supply studies into wider societal discussions, making the invisible visible—how the atmosphere is used should matter to all of us. As seen in chapter one, in 1946 climatologist Helmut Landsberg was full of hope for how climate, a resource, could be used to benefit ordinary people in an exciting

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[32] Vladimir Janković and Andrew Bowman, “After the Green Gold Rush: The Construction of Climate Change as a Market Transition,” *Economy and Society* 43, no. 2 (April 3, 2014): 233–59.

[33] Russell Hitchings, “Seasonal Climate Change and the Indoor City Worker,” *Transactions of the Institute of British Geographers* 35, no. 2 (2010): 282–98.

[34] This invisibility is perhaps reflected by the fact that the author could not source photographs of two of the main actors in this story—Paul Schiller and Maurice Davies—and in the case of the latter even faced difficulty in finding his given name.

egalitarian nuclear future.[35] Perhaps it is time to revisit more Landsbergian hopes for the atmosphere, which are inseparable from visions for a better society.

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[35] Landsberg, “Climate as a Natural Resource.”

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Appendices

The following appendices provide greater detail on the mathematical bases of weather-based forecasting techniques used by practitioners within the gas and electricity industries.

Appendix A: Mathematical Approach of Schiller

Using regression techniques, Schiller was able to achieve his aim of separating the lighting load from the space heating load. For the lighting relationship, Schiller used logarithmic regression, citing unpublished measurements of the late afternoon peak as evidence that the curve would be logarithmic in character. Schiller found that the load followed a three-dimensional surface given by the equation:

$$L = 33.74 - 1.9 \log i - 0.29t$$

where *L* is the load in megawatts, *i* is the illumination in foot-candles, and *t* is the temperature in degrees Fahrenheit. To isolate the lighting and space heating relationships, Schiller simply had to take *i* or *t* as constants. As an afterthought, Schiller added wind as a variable to create the four-dimensional load surface given by:

$$L = 33.68 - 1.96 \log i - 0.3t + 0.06w$$

where *w* is the windspeed in miles per hour.

Appendix B: Mathematical Approach of Davies

Effective Temperature: Starting from a first-order lag equation, Davies derived a recurrence relationship between the unheated indoor temperature, outdoor temperature, and unheated indoor temperature at a previous time. He then simply applied the recurrence relation to historical datasets, using a cut and try method to determine the optimum thermal lag constant, the fitness of which he measured by undertaking regression analysis with the system load. From this, Davies was able to extract an optimum thermal lag constant of twenty-two hours, leading to the equation:

$$T_E = 0.045T_0 + 0.955T_{E-1}$$

where T_E is effective temperature, T_{E-1} is the effective temperature one unit of time previously, and T_0 is outdoor temperature. For operational purposes in 1992, T_{E-1} denoted the effective temperature twenty-four hours previously, and the T_0 was the average outdoors temperature for the preceding four hours.

Daylight Illumination Index: Firstly, Davies wished to investigate the behaviour of daylight illumination under cloudless conditions. While attempting this, it was noticed that there was a strong relationship between visibility, measured as a distance by the Meteorological Office, and illumination, which Davies tabulated for future operational use. Using the reciprocal of this relationship, Davies was able to normalise measurements based on infinite visibility, allowing him to tabulate the relationship between solar elevation and illumination. Next, Davies looked at the complex interaction between cloud and illumination. *The Daily Weather Report* for 1955 indicated the type of cloud (e.g. tufted Cirrus increasing and thickening), as well as the coverage in $\frac{1}{4}\pi$ steradians (oktas) and the altitude for the main layer and the lowest layer. Using the results of theoretical physicists such as Arthur Schuster with regard to scattering media, Davies was able to construct a model for determining the transmission through multiple layers of cloud.

Cooling Power of the Wind: Drawing on research regarding heat loss from a number of "bodies", including buildings, lightbulbs and actual human bodies, Davies believed that the heat loss equation had to be of the form:

$$W^m(T_s - T)$$

where *W* was windspeed, T_s was the temperature of the body, *T* was the ambient (outdoor) temperature, and *m* was a constant. To determine the value of T_s and *m* Davies submitted the equation to regression analysis, giving values of 66°F and 0.53 respectively, which were later approximated as 65°F and 0.5 for operational purposes.

Appendix C: Mathematical Approach of Rose

Using trial and error, Rose experimented with different calculations for effective temperature. Rose assumed non-linear heat loss from houses due to convection currents, and in still air this heat loss had been found to be the temperature difference to the power 1.25. Rose claimed to have fitted curves for powers between 1.25 and 1.45, and adopted 1.4 as a “typical figure.” This led to the equation:

$$Weekday\ consumption\ in\ mill.cu.ft. = 115 + 0.96(65 - t)^{1.4}$$

where *t* is atmospheric temperature in °F. This he linearised to:

$$Weekday\ consumption\ in\ mill.cu.ft. = 115 + 0.96R$$

where *R* is $(65 - t)^{1.4}$.

Appendix D: Mathematical Approach of Turton and Harper

Turton and Harper decided against using multiple regression, instead electing to “consider one variable at a time and find the optimum solution.” This, they claimed, would allow a greater understanding of each variable and therefore greater stability in the model. Turton and Harper developed a model using the equation

$$S_D = S_{D-1} + c(\Delta T_E)$$

where S_D is the forecast daily sendout of gas, S_{D-1} is the sendout the previous day, ΔT_E is the change in effective temperature from yesterday, and *c* is a constant. Effective temperature was given as

$$T_E = aT_D + bT_{E,D-1}$$

where T_E is the effective temperature for today, T_D is the average temperature for today, $T_{E,D-1}$ is yesterday's effective temperature, and a and b are constants where $a + b = 1$.