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Histories of Balancing Demand and Supply in the UK's Gas Networks, 1795 – Present

Résumé
This paper provides an account of how past changes in energy demand have affected the balancing of the UK's gas systems between the introduction of gaslight in 1795 and the present day. Four periods are examined in which the principal uses of gas have broadly differed: periods in which the dominant uses of gas were respectively for lighting, cooking, industrial manufacture, and central heating. For each period, the paper describes how changes in the ways gas was used influenced patterns of demand and introduced opportunities and challenges for processes of balancing. Also described are how systems of gas provision were widely restructured in response to these shifts in patterns of gas demand. Three key observations are developed: that issues with balancing demand and supply are not limited to electricity networks but have been, and continue to be, critical to the organisation of gas systems; that the ways in which energy is used influence the timings (durations, frequencies, regularities), intensities, and geographies of demand and condition the balancing strategies that are possible within given contexts; and that how energy is used, and thus the composition of demand and its relationship to patterns of supply, is dynamic.

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Plan de l'article

INTRODUCTION

1 In the fields of energy provision, policy, and research, discussions over the 'flexibility' of contemporary energy systems have centred around the challenges involved in balancing dissonant patterns of supply and demand within electricity systems.[1,2,3,4] These challenges have emerged as renewable energies have progressively displaced fossil fuels within processes of electricity generation. Material differences in the ease and rapidity with which fossil fuels can be stored, transported or made to produce electricity, compared with renewable resources such as the sun, wind, and tides, have resulted in a growing disconnect between the times when electricity is most available and the times when it is most 'needed'.[5] Flexibility has consequently been considered primarily in relation to electricity systems and attention has been focused on understanding how changes in the material compositions of supply can affect processes of balancing.

2 This paper instead focuses on how changes in the composition of energy demand can influence processes of balancing. This relationship is examined through a historical case study of demand and supply within the UK's gas systems between the years 1795 (the year of coal gas's first UK commercialisation) and the present day. Like today's electricity systems, the UK's gas networks have historically experienced significant fluctuations in patterns of demand and supply and these fluctuations have created distinct challenges for processes of balancing, often bearing striking similarities with contemporary 'flexibility' concerns. As former gas engineers such as Le Fevre have, for example, noted:

> "[t]he provision of an adequate and consistent supply of gas [...] would be a comparatively simple problem if the public demand for gas were itself consistent. But unfortunately, it is far from being consistent. Like all other public requirements, it is subject to rush-hours (periods of peak demand), while being equally prone to slack or off-peak periods".[6] 3

Moreover, 'flexibility' has itself often been explicitly invoked as a potential solution to these issues. Smith, for example, writing: 4

> "So we come to the second fundamental of gas distribution – the fact that the system must be sufficiently flexible to meet the many and varied demands likely to be made upon it".[7] 5

Today, gas is primarily used in the UK for domestic cooking and heating (32.07%), electricity generation (28.31%), and in industrial and commercial applications (20.76%).[8] In the past, however, it was used in a much wider range of activities, including lighting, transport, refrigeration, ironing, hair drying, image projection, and even powering radios.[9] In this paper, I suggest that there have been four periods since 1795 in which the consumption of gas became particularly closely associated with specific activities. These involved periods of prominence for gaslight (1795-1877); gas cooking (1878-1938); 6

1 David Sanders, Alex Hart, Manu Ravishankar, Joshua Brunert, *An Analysis of Electricity System Flexibility for Great Britain* (London: Carbon Trust/Imperial College, 2016).

2 Department for Business, Energy and Industrial Strategy (BEIS), *Upgrading Our Energy System: Smart Systems and Flexibility Plan* (London: BEIS, 2018).

3 International Energy Agency (IEA), *Energy Transitions in G20 Countries: Energy Transitions Towards Cleaner, More Flexible, and Transparent Systems* (2018). URL: https://webstore.iea.org/energy-transitions-in-g20-countries-energy-transitions-towards-cleaner-more-flexible-and-transparent-systems (accessed 22/6/20).

4 Antony Froggatt, Daniel Quiggin, *The Power of Flexibility: The Survival of Utilities During the Transformations of the Power Sector* (London: Royal Institute of International Affairs, Chatham House, 2018).

5 Philip Grunewald and Marina Diakonova, "Flexibility, Dynamism and Diversity in Energy Supply and Demand", *Energy Research and Social Science*, n°38, 2018, 58-66.

6 R. Le Fevre, *Gas Distribution Engineering: The Principles for Students* (London: Walter King Ltd., 1948), 2.

7 Norman Smith, *Gas Manufacture and Utilization* (London: The British Gas Council, 1945), 85.

8 Department for Business, Energy and Industrial Strategy (BEIS) *Digest of UK Energy Statistics (DUKES): Natural Gas* (London: BEIS, 2019). URL: https://www.gov.uk/government/statistics/natural-gas-chapter-4-digest-of-united-kingdom-energy-statistics-dukes (accessed 06/07/20).

9 Examples of these devices can be viewed at the National Gas Museum in Leicester.

industrial manufacture (1939-1959); and gas-fired domestic central heating (1960-present). Whilst none of these periods involved a totalising shift towards a single application, each reflects a trend towards a dominant way of using gas. I show how these shifting trends have resulted in major alterations to the temporal and spatial characteristics of gas demand and have thereby introduced new opportunities and challenges for processes of balancing; opportunities and challenges that have often been associated with repeated and dramatic reconfigurations of gas's systems of provision.

7 In documenting these historic patterns of demand and supply, the paper draws on written evidence from the UK's National Gas Archives. This material includes articles from industry journals, internal company documents (annual reports, company procedures, operational manuals, archived correspondence), historic legislation, and published secondary histories. Three observations are developed from analysing this material: 1) that issues concerning the balancing of demand and supply are not limited to electricity systems but have been, and continue to be, critical to the organisation of gas systems (albeit often for different reasons and involving different timescales); 2) that how energy is used influences the timings (durations, frequencies, regularities), intensities, and geographies of peaks and troughs in energy demand and can introduce new opportunities and challenges for processes of balancing; and 3) that the composition of energy demand is dynamic: its timings, intensities and geographies shift as the uses of energy change.

8 The paper proceeds as follows. Section 2 describes the period between 1795 and 1877 when gas was primarily used for artificial lighting. Section 3 focuses on the years between 1878 and 1938, when gas was mainly used for cooking. Section 4 examines the period between 1939 and 1959, when gas was predominantly used within industrial processes. And section 5 describes the increase in domestic central heating that took place from the 1960s. The paper concludes with a reflection on the consequences of these examples for conceptualising processes of balancing.

GASLIGHT (1795 – 1877)

The first instance of a methane-based gas being used within commercial applications in the UK was in 1795, when industrial gas-lighting systems were commissioned at Neath Abbey ironworks (South Wales) and at a factory in Old Cunnock, Ayreshire (Scotland).[10] Known as 'coal gas', this fuel was produced by baking coal in retorts that isolated it from oxygen,[11] and it was initially used principally for lighting mills and factories. Coal gas offered significant advantages over candles, producing a stronger light that was less susceptible to starting fires.[12] The consequent reduction in fire risk lowered insurance premiums and helped to offset the high cost of gaslighting equipment.[13] 9

It was these costs that meant that, apart from one or two affluent enthusiasts, the initial producers and consumers of coal gas were almost exclusively mills and factories. This began to change in 1814 with the opening of the first public gasworks in London, the purpose of which was to produce and distribute gas to private consumers for the purposes of lighting.[14] At first, these consumers were limited to affluent individuals and local councils, the latter using it to deliver the new public service of streetlighting.[15] However, as 10

10 Experiments using gases for energy services began much earlier, in locations other than the UK. 1795 only marks the commissioning of the first gaslight system for commercial use. The more concerted marketing of gaslight took place from 1802 onward, mainly through the campaigning of Frederick Winsor. For more information, see: Everard Stirling, *The History of the Gas Light and Coke Company 1812-1949* (London: A&C Publishers Ltd., 1992 [1949]).
11 Samuel Hughes, *A Treatise on Gas-Works and the Practices of Manufacturing and Distributing Coal Gas* (London: Lockwood & Company, 2010 [1871]).
12 John Maiben, *A statement of the advantages to be derived from the introduction of coal gas into factories and dwelling houses, as a substitute for the lights now in use: together with observations on the method of making and using it* (Perth: John Maiben & Company, 1813).
13 Malcom Falkus, "The Early Development of the British Gas Industry, 1795-1815", *Economic History Review*, vol. 35, n° 2, 1982, 217-234.
14 Stirling, *The History* (cf. note 10).
15 John Wilson, *Lighting the Town: A Study of Management in the North West Gas Industry 1805-1880* (London: Paul Chapman Publishing Ltd, 1991).

further gasworks opened and expanded, the price of coal gas fell and domestic gaslighting became increasingly widespread.[16] The manufacturing and distribution systems for coal gas subsequently became known as 'town gas networks', each typically serving a single town or district and consisting of an array of buried pipes that connected dispersed consumers to a central gasworks. By 1819, town gas networks had been established in the cities of Bath, Birmingham, Bristol, Cheltenham, Edinburgh, Exeter, Glasgow, Leeds, Liverpool, London, Preston, and Manchester.[17] By 1882, this number had risen to over 500.[18]

11 Even before the debut of town gas networks however, challenges had emerged concerning the balancing of demand and supply for gas. In mills and factories (as within town networks from 1814 onward), artificial light was generally required only during the hours of darkness and daily demand was characterised by a pronounced evening peak.[19] Conversely, patterns of production required consistency across the day. Manufacturing processes were often slow to start, with retorts taking time to heat up. These devices also did not react well to rapid alterations in operating procedures and gas workers therefore had to gradually heat their retorts and produce gas over extended periods.[20] This resulted in a diurnal disconnect between the timings of peak gas demand and the timings of supply.

12 In 1805, gasholders were developed in response to this tension.[21] Gasholders were a simple form of gas storage that consisted of gas-tight containers. Their deployment enabled gas to be produced at a constant rate (gas being stored across the day) and then rapidly withdrawn as peaks in demand developed. Their deployment marked a notable shift in operational approach. Previously, manufacturing plant had been sized around a maximum level of *momentary demand,*[22] but now the scaling of these facilities became framed around a calculated level of maximum *daily demand.*[23] Gasholders were therefore built to be of "sufficient capacity to contain the maximum quantity of gas produced in twenty-four hours".[24]

Yet, whilst this new scaling helped to balance the diurnal disconnect between the timings of demand and production, it also introduced a problem. As the principal use of gaslight shifted from mills and factories to houses and streets, demand for gas grew rapidly. However, because gas systems had been sized around a static calculation of maximum daily demand, the scale of gasholders, pipes and workforces became increasingly inadequate for balancing gas supplies with the growing intensities of demand. Almost everything about town gas networks consequently had to be resized once demand reached a certain level. Necessary alterations were often extensive, including enlargements to the diameters of distribution pipes, increases in the number and size of gasholders and retorts, and the recruitment of larger workforces.[25] 13

Moreover, during this period, town gas networks began to experience issues with seasonal fluctuations in demand. Hours of darkness in the UK vary across the year, with summers being 14

16 Stirling, *The History* (cf. note 10).
17 British Gas, *Gas Chronology: The Development of the British Gas Industry* (London: British Gas, 1980).
18 Malcolm Peebles, *Evolution of the Gas Industry* (New York & London: New York University Press, 1980).
19 Smith, *Gas Manufacture and Utilization* (cf. note 7).
20 Douglas Copp, *Gas Transmission and Distribution* (London: Walter King Ltd, 1967).
21 Leslie Tomory, "Fostering a new industry in the Industrial Revolution: Boulton & Watt and gaslight 1800–1812", *The British Journal for the History of Science*, vol. 46, n°2, 2013, 199-229.
22 Momentary demand' is an engineering term that refers to the volume of gas exiting a gasworks in a given moment, as a result of its consumption or release across the network. See, for example, Le Fevre, *Gas Distribution Engineering* (cf. note 6). However, this figure rarely reflects the total demand occurring across the network in a given instant. Due to the slow movement of gas, and because a surplus of gas is stored gas within pipes, there is often a significant lag between when gas is consumed and when it leaves a gasworks.
23 Despite this, the size of gas distribution equipment still had to be "sufficient to cope with the maximum momentary demand" - Le Fevre, *Gas Distribution Engineering* (cf. note 6).
24 Hughes, *A Treatise on Gas Works* (cf. note 11), 195.
25 *Id.*

characterised by longer periods of daylight than winters. As a result, demand for gaslight assumed a strongly seasonal character, peaking in midwinter and declining to almost nothing during summer months.[26] Whilst similar fluctuations had affected mills and factories before, the increasing scale of town gas networks rendered seasonality a more pressing issue. Having invested heavily in higher-capacity plant and larger workforces, town gas networks were faced with regular forms of infrastructural and labour redundancies, as levels of gas demand dramatically declined during the summer.[27] Gasholders had limited value in managing these fluctuations because they had been scaled around demand fluctuations over the timescales of days, not around longer durations such as weeks and months. Gas companies therefore had to develop alternative approaches to balancing, the most common involving operating existing plant at reduced loads during the summer (at the expense of efficiency), and/or relying upon seasonal workforces.[28] Indeed, until at least 1911, many gas workers were only employed during winter months.[29,30,31]

COOKING (1878 – 1938)

15 Between 1878 and 1938, the dominant use of gas broadly shifted from lighting to cooking. This was closely associated with the introduction of electric light, which despite experiments with arc lighting during the early 1800s, only became commercially viable with the invention of the incandescent lightbulb in 1878. Electric light first entered the UK's lighting markets in 1879,[32] but it didn't become widely available until the metal filament had been invented (1911) and after that, when the UK's Electricity (Supply) Act had been passed (1926). Despite this slow start, it was clear by 1878 that the brighter, cleaner light promised by electric lighting would present gaslight with significant competition.[33]

16 By 1878, a mature, nationally regulated coal gas industry had developed, consisting of a multitude of organisations involved in manufacturing and distributing coal gas, developing appliances, and maintaining consumer installations. This industry responded to the emerging competition from electricity in two ways. First, it took efforts to improve gaslight's competitiveness relative to electric light, culminating in the UK launch of the first Welsbach incandescent mantles in 1887.[34] These devices fitted over existing gas lamps and produced a comparable light to electric bulbs. They were comparatively inexpensive and easy to install, and they required no new wiring or appliances. As such, they offered a compelling alternative to electric light and they have since been credited with slowing the rate of gaslight's demise.[35]

17 The gas industry's second response was to diversify the markets for coal gas. Attempts at this had begun in 1824 with the release of the first gas cookers, followed by a series of high-profile demonstrations in the following years.[36,37] Diversification was only really pursued in earnest after 1900 however, as competition from the nascent electricity industry began to develop. Efforts to facilitate this included the formation of the Society of British Gas Industries in 1905 (which supported the interests of appliance developers), the creation of

26 Smith, *Gas Manufacture and Utilization* (cf. note 7).
27 *Id.*
28 Leslie Tomory, "Building the First Gas Network, 1812—1820", *Technology and Culture*, vol.52, n°1, 2011, 75-102.
29 Zerah Colburn, *The Gasworks of London* (London: Bucklersbury, 1865).
30 Frederick Dolman, "Municipalities at Work", *The New Review,* vol.11, n°62, 1894, 74-86.
31 Frank Popplewell, "Seasonal Fluctuations in Employment in the Gas Industry", *Journal of the Royal Statistical Society,* vol. 74, n°7, 1911, 693-754.
32 First in Liverpool in 1879, then nationally in 1882. See: UK Government, *Liverpool (Corporation) Electric Lighting Act* (London: UK Government, 1879); UK Government, *Electric Lighting Act* (London: UK Government, 1882).
33 Peebles, *Evolution of the Gas Industry* (cf. note 18).
34 Named after Carl Auer von Welsbach who had patented the first incandescent gas mantle in Paris in 1885. See: John Stock, "Carl Auer von Welsbach and the Development of Incandescent Gas Lighting", *Journal of Chemical Education,* vol. 68. n°10, 1991, 801-803.
35 J. Terrace, *Terrace's Notebook for Gas Engineers and Students* (London: Ernest Benn Ltd, 1948).
36 British Gas, *Gas Chronology* (cf. note 17).
37 Sara Pennell, *The Birth of the English Kitchen, 1600-1850* (London: Bloomsbury, 2016).

the Gas Heating Research Committee in 1907, and the establishment of the British Commercial Gas Association in 1911.[38] This latter entity served as a centralised publicity agency for the British gas industry, promoting the benefits of new gas appliances.[39]

18 Two shifts in patterns of gas demand occurred in conjunction with these developments. First, the use of gaslight declined dramatically, accounting for just 5% of the UK's total gas sales by 1939.[40] Second, the use of gas for cooking and water heating dramatically increased. Such was the strength of this growth that overall demand for gas grew and cooking became the new principal use of gas. Demand for gas-fired space heating remained limited during this period due to gas's high price relative to other solid heating fuels such as coke and coal[41] (Robinson, 1956). Figures 1 to 4 represent these shifts in demand patterns, each depicting an average daily demand profile for a typical London town gas network between 1899 and 1927.[42]

19 These changes in gas demand introduced new opportunities for balancing gas networks. The shift to gas cooking brought about a decline in seasonal swings in gas demand (the result of cooking practices being performed relatively consistently across the year).[43] This reduced the need for

Figure 1: In 1899, gas was principally used for lighting and daily demand reflected periods of daylight. Peak demand occurred in the early evening (~7pm), tailing off towards midnight, as people went to bed. A baseload demand remained overnight due to gas being used for streetlighting. Source: R. Le Fevre, *Gas Distribution Engineering: The Principles for Students* (London: Walter King Ltd, 1948, 4-5. All rights reserved).

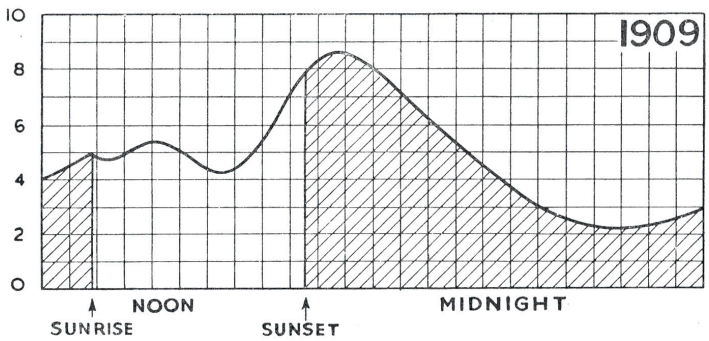

Figure 2: By 1909, gas cooking had become more common, but lighting remained the principal use of gas. The largest peaks were defined by the hours of day and night, but demand was now consistently higher across the day due to gas being used in food preparation. A small midday peak emerged as gas became used for lunchtime cooking. At night, demand levels remained roughly the same, with gas being used for streetlight. Source: R. Le Fevre, *Gas Distribution Engineering: The Principles for Students* (London: Walter King Ltd, 1948, 4-5. All rights reserved).

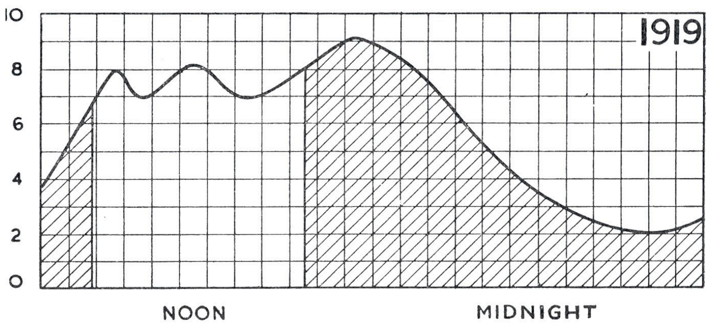

Figure 3: By 1919, overall gas demand had risen as a result of the growth of gas cooking. Gas was used more consistently across the day, but three peaks had also begun to develop around the morning, lunchtime, and evening mealtimes. The evening peak was more pronounced than others due to the continued use of gaslight. Source: R. Le Fevre, *Gas Distribution Engineering: The Principles for Students* (London: Walter King Ltd, 1948, 4-5. All rights reserved).

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38 British Gas, *Gas Chronology* (cf. note 17).

39 Charles Hastings, "British Commercial Gas Association", *The Gas Engineer's Magazine*, vol.29, n°441, 1913, 277-278.

40 Hugh Barty-King, *New Flame: How Gas Changed the Commercial, Domestic and Industrial Life of Britain Between 1813 and 1984* (Tavistock: Graphmitre Ltd, 1984).

41 H. Robinson, "Radiant Heating – Past, Present and Future" *British Junior Gas Associations Joint Proceedings 1955-56*, vol. XXXIX, 1956, 720-724.

42 These images have been reproduced from: R. Le Fevre, *Gas Distribution Engineering: The Principles for Students* (London: Walter King Ltd, 1948, 4-5. All rights reserved). Several identical images also appeared in the earlier text: Norman Smith, *Gas Manufacture and Utilization* (London: The British Gas Council, 1945, 86-87. All rights reserved). I have been unable to identify the original source.

43 Gas networks would often still experience some, minor, seasonal fluctuations in load due to the continuation of some gaslight and heating activities.

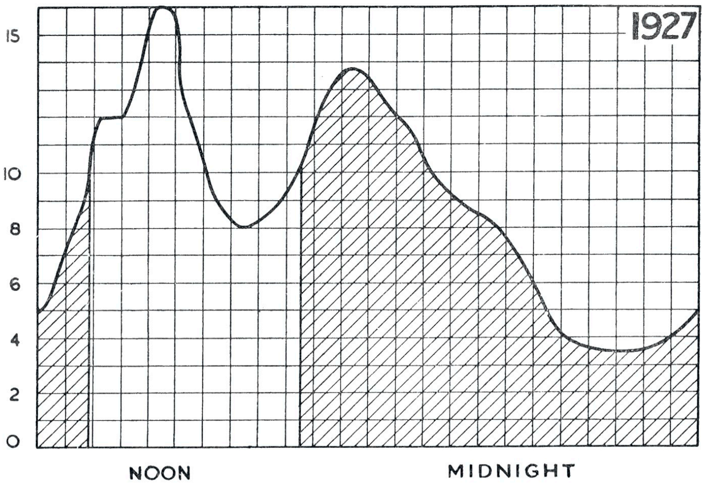

Figure 4: By 1927, gas cooking had exceeded gaslight as the main use of gas and overall gas demand had risen significantly. Daily demand peaks reflected mealtime conventions, but the most pronounced peak now occurred at noon, coinciding with the then-traditional timing of the main daily cooked meal[44]. Gaslight continued to be used at night. Source: R. Le Fevre, *Gas Distribution Engineering: The Principles for Students* (London: Walter King Ltd, 1948, 4-5. All rights reserved).

seasonal labour[45] and brought about a shift in how coal gas was both valued and made.[46] Coal gas had previously been sold for its illuminating power (a measure of the amount of light that its combustion would produce), but the shift to gas cooking, in combination with the turn to using incandescent mantles,[47] resulted in gas instead being valued for the amount of heat that its combustion produced (measured in terms of its 'calorific value').[48] This was significant for processes of balancing because it removed earlier limitations to processes of gas-making. Previously, the production of highly luminescent gas had "dictate[d] the type of gas-making plant employed, the kind of coal used, and the conditions of operation".[49] Indeed, it required highly specific raw materials[50] and had placed restrictions on the kinds of production methods that could be employed. The requirements for producing gas with a high thermal output were much less stringent, allowing for a wider range of coal types to be used and vertical, rather than horizontal, retorts to be employed. These latter devices allowed gas to made continuously, rather than production being regularly interrupted as spent coal was removed and fresh coal was introduced.[51]

Perhaps most significantly however, the shift to 20
manufacturing gas for its calorific value permitted the deployment of a new strategy known as 'peak shaving'. This involved the rapid production of large volumes of gas with a low calorific value (gas that produced less heat when burnt). This could then be enriched with small quantities of a higher-calorie supplement, such as gasified oil or butane, which would boost the calorific value of the overall gaseous mixture and thereby enable larger volumes of gas with a similar-to-normal calorific value to be quickly produced.[52] Peak shaving meant that gas production could be rapidly ramped up during periods of peak demand, albeit at a cost to efficiency. It subsequently became a routine part of balancing town gas networks, with most gasworks installing new plant that was dedicated to producing high volumes of lower-calorie gases that could then be enriched. Two methods became common: the production of 'producer gases' and the manufacture of 'water gases. Although resulting in gases with different qualities and characteristics, both involved the introduction of steam to heated coke and involved harnessing of the

44 Today, it is more common for main meals to be eaten in the evening. See: Alan Warde and Luke Yates, "Understanding Eating Events: Snacks and Meal Patterns in Great Britain", *Food, Culture & Society,* vol. 20, n°1, 2017, 15-36.

45 Seasonal employment was still in use in 1911 but at a reduced level. It also continued to decline over this period. Retort workers were the worst affected by seasonal demand patterns. See: Popplewell, *Seasonal Fluctuations* (cf. note 31).

46 Smith, *Gas Manufacture and Utilization* (cf. note 7).

47 Incandescent mantles worked by their materials emitting light when heated. This meant that they relied on gas for the heat it produced, not its light output. See: Terrace, *Terrace's Notebook* (cf. note 35).

48 See: UK Government, *Gas (Standard of Calorific Power) Act* (London: UK Government, 1916); UK Government, *Gas Regulation Act* (London: UK Government, 1920).

49 Terrace, *Terrace's Notebook* (cf. note 35), 52.

50 This had become an issue during the first world war (1914-18), as the availability of these specific coals declined. See: Terrace, *Terrace's Notebook* (cf. note 35).

51 *Id.*

52 E. Ward, *Gasmaking* (London: The British Petroleum Company Ltd, 1959).

subsequent reaction to produce large volumes of gas quickly.[53]

21 Yet, the turn to gas cooking also created challenges for balancing, however. In particular, it resulted in particularly intense but infrequent peaks in demand on Sundays and on special days, such as Christmas and Easter.[54] During this period, it was traditional to prepare roast dinners on these occasions and the associated increase in gas consumption could create intense, but infrequent, demand peaks. These peaks presented balancing challenges concerning infrastructural redundancy, typically described in terms of 'network load factors': calculations of the disparity between the average and maximum rates of gas demand.[55,56] If a network was designed to accommodate high rates of momentary demand that only occurred infrequently, much of the added capacity would prove redundant during more ubiquitous periods of lower demand, resulting in a poor load factor.[57,58] Poor load factors could affect gas prices and depress overall demand.

22 Load factor issues manifested in two ways during this period. First, Sunday demand could exceed the total volume of gas supply available, and whilst this could technically be solved by investing in extra peak-load plant or more storage capacity, the infrequency of peaks meant that these infrastructures "would be used only for a few hours weekly, and for the remainder of the week would remain idle".[59] This could make such investments uneconomical. A second problem then related to how distribution systems were not always sufficiently sized to deliver gas in the necessary volumes to all consumers during peak periods.[60] Friction from the pipe walls could limit the amount of gas reaching properties at a given moment, resulting in gas pressures "too low to give the requisite heat input into the ovens of the cookers".[61] Customers worst affected were often those located at the extremities of gas networks and, as a result, balancing challenges began to assume a distinctly geographical dimension. Whilst this issue could be solved by increasing pipe diameters (reducing friction relative to gas volume), it would often be detrimental to load factors because of the cost of replacing pipework.[62] Two alternative strategies developed during this period were to install booster equipment to raise gas's pressure (and speed) across networks,[63] and to build cheaper 'static' gasholders near to network extremities. These devices made it possible to store gas close to locations of demand so that it did not have as far to travel to reach consumers in time. They would typically be filled up during mid-week demand troughs.[64]

A final geographical complication that emerged during this period concerned the greater geographical variability of gas cooking demand compared to the earlier demand for gaslight. Networks that supplied seaside resorts were especially affected, these locations often experiencing seasonal peaks during the summer, as large numbers of caterers used gas to prepare food for holidaymakers. These geographically specific peaks in demand rarely caused issues for balancing however, for they often 'evened out' disparities between winter and summer gas loads, helping to reduce seasonal load factors. As Coe writes: 23

53 Alexander Humboldt-Sexton, *Producer Gas: A sketch of the properties, manufacture, and uses of gaseous fuel* (Manchester: Scientific Publication Company, 1905). A. Parker, "The Manufacture of Blue Water Gas", *Nature*, vol.115, 1925, 501–502. Ward, *Gasmaking* (cf. note 51).

54 Sunday roasts have since declined in popularity but remain a widespread UK tradition. See: Nestle Family Monitor (NFM), *Eating and Today's Lifestyle* (London: Carried out by MORI on behalf of Nestle UK, 2001); Mintel, *Changing British Diet – UK –May 2003* (London: Mintel International Group, 2003); Andy Gatley, Martin Caraher, Tim Lang, "A qualitative, cross cultural examination of attitudes and behaviour in relation to cooking habits in France and Britain", *Appetite*, vol.75, 2014, 71-81.

55 Le Fevre, *Gas Distribution Engineering* (cf. note 6).

56 Smith, *Gas Manufacture and Utilization* (cf. note 7).

57 *Id.*

58 Copp, *Gas Transmission and Distribution* (cf. note 20).

59 Smith, *Gas Manufacture and Utilization* (cf. note 7), 105.

60 *Id.*

61 *Id.*

62 *Id.*

63 A. Langford, "Methods for Reducing District Complaints", *British Junior Gas Associations Joint Proceedings 1933-34*, vol. XXIV, 1933, 283-288.

64 Smith, *Gas Manufacture and Utilization* (cf. note 7), 105.

24 "At seaside resorts both the maximum daily load, and the maximum hourly peak load occur in summer, so that heating of every kind of premises, and in fact all purely winter loads, do not increase either of these demands, and public lighting has but a negligible effect upon the maximum daily load".[65]

INDUSTRIAL MANUFACTURE (1939 – 1959)

25 With the commencement of the second world war, overall demand for gas fell. National air raid blackouts reduced the demand for gaslight and demand for gas-based cooking and heating activities similarly declined as the price of gas rose in response to wartime coal shortages.[66] These trends also continued after the war. Damaged gaslight infrastructures were widely replaced with electric lights and gas became increasingly perceived as old fashioned, dirty and poisonous.[67,68] Moreover, the price of gas remained high relative to other fuels, increasing on average by 67% between 1950 and 1959[69] as a result of the continuing high cost of coal, the extent of post-war infrastructural repairs, and the fact that many gasworks had been left only with gas-making plant that had been designed for peak shaving. Indeed, peak load plant became widely used in manufacturing gas for base loads, reducing the efficiency of production and increasing gas prices. Domestic demand continued to stagnate as a result.[70,71]

At the same time, however, the war stimulated growth in industrial gas demand.[72] Industrial gas consumption was not new to this period. Gas had first become widely used in manufacturing processes during the 1930s, following the shift to high thermal output gases that were better suited to industrial applications.[73,74,75] However, the production of wartime apparatus stimulated major growth in this form of gas usage however, to the extent that industrial demand quickly exceeded the falling levels of domestic gas consumption.[76] Combined with the sale of by-products for military applications, this increase enabled many gas companies to stay afloat during this period. Strategies employed for balancing varied dependent upon individual network loads, but they typically involved a combination of storage, variable production and peak shaving.[77] 26

With the close of the war, wartime production then ceased, and industrial gas demand went into sudden decline.[78] Gas cooking consequently resurfaced as the dominant use of gas and demand again assumed its previous daily and weekly peaks. Balancing was performed using the same strategies as had been employed during the 1930s, but the combination of lower levels of domestic demand, reduced industrial demand, and the need for urgent widespread infrastructural repairs resulted in many gas networks facing collapse by 1948. In response to this crisis, the gas 27

65 Arthur Coe, *The Science and Practice of Gas Supply Volume III, Including the Economics of Gas Supply* (London: The British Commercial Gas Association, 1939), 1376.
66 E. Brooks, "Thermal Environment and Comfort in the Home: Progress, Procrastination, and Probable Trends", *Institution of Gas Engineers Journal*, vol.10, 1970, 523-537.
67 Town gas often had a high carbon monoxide content and its inhalation could prove fatal. It consequently became a common method of suicide. See: Wolfgang Schivelbusch, *Disenchanted Night: The Industrialisation of Light in the Nineteenth Century* (California: University of California Press, 1983).
68 Barty-King, *New Flame* (cf. note 40).
69 J. Ellis, "Industrial Gas in Birmingham", *British Junior Gas Associations Joint Proceedings*, 1959-1960, pp.689-720.
70 Ward, *Gasmaking* (cf. note 51).
71 R. Deans, "The Value of the Space Heating Load", *British Junior Gas Associations Joint Proceedings 1952-53*, vol. XXXVI, 1952, 861-875.
72 J. Oates, "Presidential Address, Manchester Association General Meeting, 17th October 1953", *British Junior Gas Associations Joint Proceedings 1953-54*, vol. XXXVII, 1953, 261-270.
73 P. Lloyd, "Industrial Gas Heating", *British Junior Gas Associations Joint Proceedings 1933-34*, vol. XXIV, 1933, 218-239.
74 K. Langford, "Economics of Gas in Industry", *British Junior Gas Associations Joint Proceedings 1933-34*, vol. XXIV, 1933, 425-434.
75 G. Windiate, E. Craddock, "The Application of Town Gas to Industrial Heating Problems", *British Junior Gas Associations Joint Proceedings 1934-35*, vol. XXV, 1934, 110-113.
76 Oates, *Presidential Address* (cf. note 72).
77 *Id.*
78 *Id.*

Figure 5: Map of the UK's gas boards following nationalisation. Source: K. Hutchinson, "The Future of the Gas Industry in Great Britain", *Institution of Gas Engineers Journal,* vol. 6, 1966, 538. Image reproduced with permission from IGEM.

industry was nationalised in 1949.[79,80] The large number of privately and municipally owned town gas networks were consolidated into 12 new area boards and these were overseen by a national Gas Council (Figure 5). Under this arrangement, much of the damaged gas infrastructure was repaired and local gas networks were linked together to form 12 regional gas 'grids'.[81]

79 K. Hutchinson, "The Future of the Gas Industry in Great Britain", *Institution of Gas Engineers Journal,* vol. 6, 1966, 537-552. The coal and electricity industries were also nationalized in 1946 and 1947, respectively.

80 UK Government, *Gas Act* (London: UK Government, 1948).

81 Hutchinson, *The Future of the Gas Industry* (cf. note 79).

28 These changes introduced the possibility of new strategies for balancing demand and supply in real time. Integrating town gas networks allowed gas boards to share production and storage capacity across regional grids, improving the efficiency with which demand and supply could be balanced. This reduced manufacturing costs significantly.[82] Rather than individual gasworks varying their outputs to meet localised demands, select sites could provide gas only for regional base loads, producing larger volumes of gas more efficiently.[83,84] Other sites could be used to produce gas for peak load requirements.[85] In combination, this resulted in a significant decline in the number of gasworks required across the UK. Between 1948 and 1965, the number of UK gasworks fell from 1050 to just 246, resulting in significant savings in the costs of manufacture.[86] Many former gasworks were converted into gasholder stations, allowing area boards to retain their gasholder storage for the purposes of diurnal balancing.[87]

29 Whilst this arrangement enabled more effective load management and reductions in operating costs, it also required careful planning for balancing to be effective. The integration of multiple town gas networks with varying consumers and loads caused the geographical distribution of demand to become increasingly complex across regional grids. In the process, issues with the sizing of distribution pipes and their abilities to satisfy geographically specific peaks in demand re-emerged. In the process, the location of sites of gas production (in particular, peak load plants), became increasingly significant to balancing processes.[88]

Furthermore, despite these new forms of efficiency, poor load factors continued to present challenges for balancing. Distribution systems still had to be sized to meet the intense but infrequent Sunday peaks in demand. Combined with high levels of infrastructural investment and stagnating gas sales, this meant that gas prices remained high, further supressing overall demand for gas and preventing it from being competitive in the fast-growing post-war market for domestic central heating.[89,90] 30

During this period, gas boards consequently attempted to improve their network load factors by attracting new industrial and commercial consumers who promised loads that effectively 'filled in' troughs in demand.[91,92] This involved gas boards offering gas at cheaper rates, often to companies who only used gas during weekdays. Indeed, between 1950 and 1959, this initiative stimulated significant growth in industrial gas demand.[93,94,95,96,97,98] In conjunction, many gas networks experienced an inversion 31

82 K. Summersgill, "Some Aspects of Grid Interlinkage", *British Junior Gas Associations Joint Proceedings 1953-54*, vol. XXXVII, 1954, 365-385.
83 R. Jones, "The Chemical Control of Modern Base Load Works", *British Junior Gas Associations Joint Proceedings 1956-57*, vol. XXXX, 1956, 810-811.
84 A. Yeaman, "Carbonisation on Base Load Works", *British Junior Gas Associations Joint Proceedings 1957-58*, vol. XLI, 1957, 834-854.
85 Summersgill, *Some Aspects* (cf. note 82).
86 Hutchinson, *The Future of the Gas Industry* (cf. note 79).
87 R. Langford, "Planning Small Holder Stations to Reduce Operation and Maintenance Costs to a Minimum", *British Junior Gas Associations Joint Proceedings 1960-1961*, vol. XLIII, 1961, 42-52.
88 Summersgill, *Some Aspects* (cf. note 82).
89 W. Moxley, "Peak Load Medium Pressure Distribution Systems", *British Junior Gas Associations Joint Proceedings 1956-1957*, vol. XL, 1956, 754-765.
90 D. Adam, "The Load Factor", *British Junior Gas Associations Joint Proceedings 1956-57*, vol. XXXX, 1957, 644-651.
91 G. Johnson, C. Taylor, "A Review of Post-War Domestic Gas Water Heating", *British Junior Gas Associations Joint Proceedings 1955-56*, vol. XXXIX, 1956, 131-166.
92 Oates, *Presidential Address* (cf. note 72).
93 *Id.*
94 J. Stretton, "The Development of Industrial Gas Sales in North Wales", *British Junior Gas Associations Joint Proceedings 1960-1961*, vol. XLIII, 1960, 473-478.
95 D. Murray, "Industrial Gas in the Central Division", *British Junior Gas Associations Joint Proceedings 1960-1961*, vol. XLIII, 1961, pp.387-390.
96 A. Higgs, "Gas is Competitive", *British Junior Gas Associations Joint Proceedings 1956-57*, vol. XXXX, 1956, 456-486.
97 K. Edwards, "The Requirements of Base Load Operation", *British Junior Gas Associations Joint Proceedings 1957-1958*, vol. XLI, 1957, 701-715.
98 R. Currie, "Selling Industrial Gas", *British Junior Gas Associations Joint Proceedings 1957-1958*, vol. XLI, 1958, 660-673.

in demand profiles such that "the gas demand on one day at the weekend [constituted] about half of the demand on one day during the working week".[99]

CENTRAL HEATING (1960 – PRESENT)

32 In contrast to the 1950s, the period between 1960 and 2020 has been broadly characterised by a marked increase in domestic gas demand, centred around the use of gas for central heating. Demand for gas-fired central heating had previously been limited due to gas's high cost relative to oil and electricity, and by 1957, it accounted for just 5-10% of domestic gas demand.[100] However, by 1965, this pattern had dramatically shifted. Knights and Allen announced that:

33 > "[t]he fantastic sales of domestic space heating appliances that have occurred over the past few years, and are expected to continue for some years to come, have drastically increased the load on gas distribution systems in this country".[101]

34 Such was this growth that demand profiles once again changed, with domestic demand making up 64% of total gas sales by 1970, compared to 21% for industrial uses.[102] Of this, 75% was for space heating.[103]

35 The reasons for this transformation have been widely attributed to the combination of a highly successful marketing campaign that presented gas as a clean, efficient, convenient, and modern space heating fuel, alongside a dramatic change in the raw materials that were used to make gas: production shifting from using coal to oil.[104] As Lawton described over a decade earlier, around this time:

> "the price of coal [had] risen steadily, and [...] oil refineries, faced with an increased demand for lighter products, [had] been forced to crack their raw materials to a greater extent, with a consequent detrimental effect on the market value of residua. The nett effect [was] that the price per therm of certain heavier grades of oil [had] not risen so sharply as the price per therm of coal".[105] 36

Shifting from coal to oil both reduced the cost of raw materials and enabled more efficient production methods, reducing the overall price of gas and rendering it more attractive to consumers.[106] 37

Sales for industrial and commercial gas consumption also remained strong during this period, and gas continued to be used for cooking.[107] The result was typical daily demand patterns that were more even than those of previous decades (Figure 6). Demand rose in the morning, with central heating systems automatically turning on before people awoke and remained consistent throughout the day. At night, it dropped off as people retired to bed. These patterns eliminated the previously problematic daily peaks in cooking demand and resulted in more efficient diurnal load factors.[108] They also enabled operators to shift to a daily rhythm of gas storage, with gas being stored overnight (as demand dropped) and it being consumed during the day[109]. 38

99 A. Pratt, E. Johnson, "Storage", *Institution of Gas Engineers Journal,* vol. 7, 1967, 603-620.
100 A. Burrell, G. Fudge, "Domestic Space Heating by Gas", *British Junior Gas Associations Joint Proceedings 1956-1957*, vol. XL, 1957, 132-149.
101 I. Knights, J. Allen, "High Speed Gas Networks", *Institution of Gas Engineers Journal*, vol. 6, 1965, 75.
102 A. Adam, G. Vasey, "Evolution of the Modern Gas Fire", *Institution of Gas Engineers Journal,* vol. 10, 1970, 797-816.
103 D. Heslop, "Central Heating: Where from – where to? Some personal reflections 1958-1978 – Part 1", *Institution of Gas Engineers Journal,* vol. 20, 1980, 99-108.
104 Hutchinson, *The Future of the Gas Industry* (cf. note 79).
105 E. Lawton, "The Manufacture of Gas from Oil: A General Review with Detailed Consideration of the 'Semet-Solvay' and 'Segas' Processes", *British Junior Gas Associations Joint Proceedings 1952-53*, vol. XXXVI, 1952, 644.
106 Hutchinson, *The Future of the Gas Industry* (cf. note 79).
107 F. Giddings, "Gas Sets the Pace" *Institution of Gas Engineers Journal*, vol. 6, 1966, 377.
108 Pratt and Johnson, *Storage* (cf. note 100).
109 R. Langford, P. Wood, "Meeting the Storage Requirements within an Area Board", *Institution of Gas Engineers Journal,* vol. 13. 1973, 129-140.

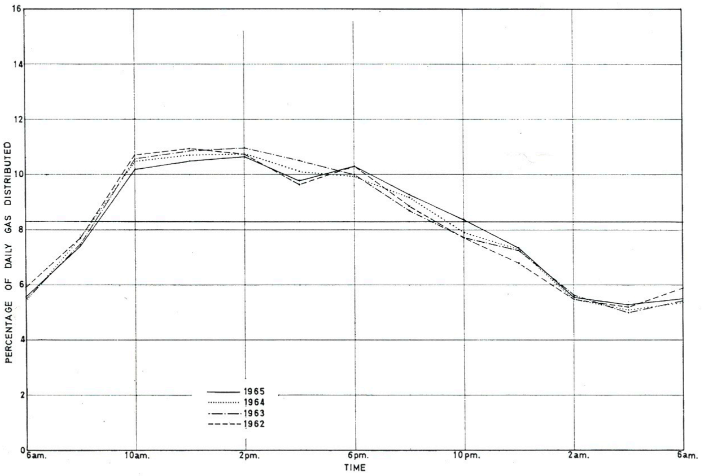

FIGURE 2.—*Variation in output, Northern Region, at 36°F.*

Figure 6: Typical daily demand profile for the Northern Region at 36 degrees Fahrenheit (1962 – 1965). Source: A. Pratt, E. Johnson, "Storage", *Institution of Gas Engineers Journal,* vol. 7, 1967, 605. Image reproduced with permission from IGEM.

39 Indeed, because gas continues to be used in broadly similar ways today, patterns of gas consumption, and the diurnal balancing strategies employed in relation to them, remain similar. The main difference today concerns the form of diurnal storage that is used to balance gas networks.[110] From 1960 onwards, the UK's 12 area grids became increasingly interconnected via high-pressure transmission pipes, allowing for gas supplies to be shared between them.[111] Unlike their lower-pressure counterparts, these new pipes could hold more gas, allowing for a surplus to be stored across gas networks. Known as 'line pack', this new form of storage grew dramatically over following decades, to the point that it eventually rendered gasholders redundant in 2014.[112] Gas continues to be stored as line pack overnight and used during the day.[113]

40 The growth in demand around gas-fired central heating developed geographically unevenly however, creating new balancing challenges for balancing. As Edwards, an engineer from the north Thames gas board, described: "[the] increase [was] not spread uniformly throughout the Board. It [was] concentrated in the residential areas at the periphery where annual increases of up to 30% [were] being experienced".[114] Because gas networks had not been sized to deliver enough gas to their peripheries to meet these new peaks, many gas boards resorted to locating new sites of production near to areas of demand, in addition to installing static gasholders near these locations. As Edwards continues,

41 > "whereas originally it was always possible to locate the production to suit the supplies of raw materials for gas manufacture, it [therefore became] both necessary and practicable to so locate them to assist the distribution system to the maximum possible extent".[115]

42 Moreover, the use of gas for space heating also brought about the return of strong seasonal demand variations that were characterised by enduring winter peaks and summer lulls. Rather than directly reflecting rhythms of daylight however, these new patterns were more closely associated with outside temperatures and meteorological conditions, rendering them more variable over the timescales of hours, days and weeks than had previously been the case with gaslight.[116,117] These seasonal rhythms, combined with the strong overall growth in gas demand experienced during this period, encouraged investment in new forms of seasonal storage, including facilities such as underground aquifers, gas wells, mines and salt caverns, as well as vessels for the storage

110 Katie Boxall, "Improving Short Term Gas Demand Forecasting", *Gas International,* November 2015, 37-39.
111 Stathis Arapostathis, *Natural Gas Network Development in the UK (1960-2010): Coping with Transitional Uncertainties and Uncertain Transitions* (Cardiff: Low Carbon Research Institute, 2011). URL: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.645.6520&rep=rep1&type=pdf (accessed 21/10/20).
112 Institute of Gas Engineers and Managers (IGEM), *Gasholders: Recording an End of an Era* (London: The British Library, 2014).
113 National Grid, *Physical Operations of the NTS and Winter Forecasting* (Webinar: National Grid, 11th September 2014).

114 E. Edwards, "Gas Supplies for the North Thames Area", *Institution of Gas Engineers Journal,* vol. 6, 1966, 633-657.
115 *Ibid.*, 634.
116 A. Buckley, "Gas Load Forecasting – A Marketing Contribution", *Institution of Gas Engineers Journal,* vol. 6, 1966, 169-181.
117 W. Roger, "What's in a Peak Day? – Alternative Uses of the Planning Model", *Gas Engineering and Management: Journal of the Institution of Gas Engineers,* July/August 1984, 269-281.

of high-calorie distillates and liquefied natural gas (LNG) for peak shaving.[118,119] Indeed, LNG storage subsequently came to play a particularly significant role in the balancing of the UK's gas networks. Major advancements were made concerning its transport, storage, and regasification, and reception terminals were built to facilitate its delivery by boat from countries such as Algeria and the United States.[120] Its increasing use for peak shaving became a major driver for the interconnection of regional grids, allowing for stored LNG to be shared between regions.[121,122]

43 Despite these measures, seasonal demand variations continued to introduce issues around seasonal load factors, with much of the capacity of gas grids becoming redundant over summer months. Gas boards therefore again sought to acquire new loads, this time aiming to fill summertime troughs in demand. As Emerson and Roberts wrote in 1968, "the industry is faced with an accentuated seasonal difference between the Winter and Summer loads [...] The acquisition of even a partial balancing load is thus a matter of urgency".[123] New loads that were pursued included hot water loads (encouraged by building boiler systems into new central heating unit, thereby promoting the simultaneous uptake of gas-fired water heating)[124], and industrial loads that had low seasonal variations. The latter were solicited by offering more favourable gas rates to eligible consumers.[125] 'Interruptible' industrial loads were also pursued during this period, in efforts to reduce the intensity of seasonal demand peaks.[126] This involved signing contracts with large consumers that had year-round demands for gas and that could switch to alternative forms of energy at short notice, if needed. Eligible companies could then purchase gas at discounted rates, knowing that their supply could be interrupted.[127,128]

Many of these strategies remain in use today, albeit adjusted to accommodate two changes in the structure of the British gas industry. The first change involved the conversion of the UK's gas systems to natural gas in the late 1970s. This resulted in the creation of an interconnected, national gas infrastructure comprised of a high-pressure national transmission system (NTS) and 6 regional distribution networks (an amalgam of the earlier gas boards).[129] 44

With the abundance of cheap domestic natural gas supplies and the higher calorific value of natural gas compared to coal or oil gas,[130] gas quickly became used in a variety of new industrial applications, most notably within electricity generation. Whilst power station loads have had a nett positive effect on the load factors of gas systems (gas typically being used during the summer, when gas prices are lower), their consumption patterns are highly dependent upon how energy is used within other energy systems. As such, the intensity of power station demand varies considerably, and this presents potential challenges for balancing gas systems. A major shift in approach to balancing since the 1970s has therefore been the increased prominence of demand forecasting. National Grid (the NTS operator) now attempts to anticipate changes in 45

118 Hutchinson, *The Future of the Gas Industry* (cf. note 79).
119 Langford and Wood, *Meeting Storage Requirements* (cf. note 110).
120 British Gas, *Gas Chronology* (cf. note 17).
121 Edwards, *Gas Supplies for the North Thames Area* (cf. note 115).
122 Hutchinson, *The Future of the Gas Industry* (cf. note 79).
123 J. Emerson, J. Roberts, "Summer Hot Water from Central Heating Boilers", *Institution of Gas Engineers Journal*, vol. 8, 1968, 365.
124 R. Holden, "Central Heating in Existing and New Property", *Institution of Gas Engineers Journal*, vol. 6, 1966, 628-629.
125 G. Thomas, "Factors Associated with and Influencing the Growth of the Industrial Gas Load in East Anglia", *Institution of Gas Engineers Journal*, vol. 6, 1966, 772-776.
126 Interruptible contracts continue to be used within both the UK's electricity and gas industries.
127 N. Bryant, "The Practical Handling of Interruptible Loads", *Institution of Gas Engineers Journal*, vol. 13, 1973, 317-324.
128 W. Howell, G. Robertshaw, "Natural Gas and the Industrial Market", *Institution of Gas Engineers Journal*, vol. 8, 1968, 780-801.
129 Charles Elliott, *The History of Natural Gas Conversion in Great Britain* (Royston: Cambridge Information and Research Services Ltd., 1980).
130 Ward, *Gasmaking* (cf. note 51).

demand within other energy systems that may affect power station loads. Analysed factors including the behaviours of electricity markets and of meteorological systems.[131]

46 Forecasting is now also the main method for managing the fluctuations in demand that result from the interconnection of the UK's gas networks with other countries' gas systems. Today, interconnector pipelines link the NTS to gas systems in Belgium, the Netherlands, Norway, Northern Ireland, and the Republic of Ireland, and these pipes allow gas to be moved between these systems more-or-less instantly.[132] This can result in sudden large fluctuations in available gas supplies that can potentially threaten the successful balancing of UK demand and supply. A key aspect of the routine day-to-day management of the NTS has therefore become the forecasting of international gas market behaviours.[133]

47 Finally, peak shaving has fallen out of use as a routine balancing strategy. The most significant reason for this is that LNG (which, since the 1960s, had become the main fuel used for peak shaving), is chemically the same as natural gas and does not have a markedly higher calorific value. As such, it cannot be used to enrich existing gas supplies. Despite this, LNG continues to play an important role in the balancing of the UK's gas system, being used more-or-less interchangeably with other natural gas supplies.[134]

48 The second major change in the structure of the British gas industry involved its return to private ownership in 1987.[135] Today, the NTS is operated by National Grid; the 6 distribution networks are overseen by multiple companies; numerous shippers purchase and sell gas supplies; storage facilities are independently operated; and different producers extract and process gas (domestic and imported natural gas, as well as domestic biomethane).[136] The whole system is regulated by Ofgem, the independent market regulator.

This arrangement has resulted in responsibility for balancing broadly shifting to the market. 49
National Grid supervises the process, but its control is limited to ensure fair market competition. It consequently has no powers over when or where gas enters the NTS, how much gas is put into it at any one time, when or where gas is put into or taken out of storage, or when and in what volumes gas is exchanged over interconnectors.[137] This marks a stark change from prior arrangements where both the production and distribution of gas was overseen by central network operators. This has also brought about several key changes in how balancing is approached.

On the one hand, diurnal demand fluctuations 50
currently present few issues for balancing. This is due to line pack allowing for peaks and troughs in demand over minutes and hours to be managed more-or-less automatically. Minor issues can still arise from dissonances in the geographical distribution of demand and supply over these timescales though, due to National Grid's commitment to permitting shippers to deliver gas into the NTS at any entry point around the country, at any time. As a result, gas demand could theoretically peak in locations where relatively small quantities of gas are stored as line pack. One of National Grid's main responsibilities is

131 Boxall, *Improving Short Term Gas Demand Forecasting* (cf. note 111).
132 House of Lords European Union Committee, *Brexit: Energy Security. 10th Report of Session 2017–2019*. (London: House of Lords European Union Committee, HL Paper 63, 2018).
133 Boxall, *Improving Short Term Gas Demand Forecasting* (cf. note 111).
134 National Grid, *Physical Operations of the NTS* (cf. note 114). The calorific value of LNG can fluctuate, dependent upon its source and the distance it must travel. Richer LNG is chemically altered to lower its calorific value in line with UK specifications. See also: D. Chrétien, "Process for the Adjustment of the HHV in the LNG Plants" (Amsterdam: 23rd World Gas Conference, 2006) URL: http://members.igu.org/html/wgc2006/pdf/paper/add10492.pdf (accessed 22/6/20).
135 Jonathan Stern, "The British Gas market 10 years after privatisation: A model or a warning for the rest of Europe?", *Energy Policy,* vol. 25, n°4, 1997, 387-392.
136 Biomethane is produced onshore using organic materials. It currently constitutes only 0.3% of UK gas supply. See: BEIS, *Digest* (cf. note 8).
137 National Grid, *Physical Operations of the NTS* (cf. note 114).

therefore to transport gas around the NTS using compressors, delivering it to areas of anticipated demand. This requires shippers declaring ahead of time when, where and in what volumes they will deliver gas into the NTS, and National Grid then forecasting the geographical distribution of demand a day ahead. This enables National Grid to anticipate patterns of future demand and supply and to move gas supplies around the country accordingly.[138]

51 On the other hand, more problematic demand fluctuations commonly manifest over longer timescales, either in relation to unexpectedly intense peaks in seasonal demand (and the associated physical unavailability of sufficient gas supplies), or market challenges that render bringing additional supplies online less profitable. One recent example of such a challenge involved successive mild winters reducing the profitability of seasonal storage, with many storage operators consequently attempting to generate smaller, faster, profits by trading gas based on day-to-day (rather than seasonal) fluctuations in gas price. This resulted in a marked reduction in the availability of winter supply reserves and fears for the security of the UK's gas supplies.[139]

52 National Grid's main approach to mitigating against these kinds of challenges is to forecast demand at different intervals (day ahead, week ahead, long term). This gives market actors the time to respond to fluctuations in demand and make additional supplies of gas available.[140] In more extreme scenarios where supply deficits look likely, National Grid can also undertake additional actions. These include providing temporary market incentives to encourage the delivery of further supplies; suspending normal market trading; and shedding interruptible loads.[141] Domestic demand-side response is reserved to only the very worst-case scenarios, taking the form of longer-term rationing (this differs from electricity rationing initiatives, which seek to shift the timings of consumption activities). Rationing is possible because, unlike electricity systems, the line pack within gas systems reduces the need to respond to short-term fluctuations in demand.[142]

BALANCING THE DEMAND/SUPPLY RELATION

In tracing these different ways in which fluctuations in demand have presented challenges for balancing within the UK's gas systems between 1795 and the present day, it is possible to draw out three observations that may inform how we understand processes of balancing dissonant patterns of demand and supply. 53

1) Issues with balancing dissonant patterns of demand and supply are critical to gas systems, not just present-day electricity networks. Within present-day discussions of 'flexibility' in the energy sector, balancing issues have been widely represented as exclusively affecting electricity systems. In this paper, I have instead described how balancing issues have repeatedly surfaced within the UK's gas networks across a 225-year period. Examining these issues reveals a series of similarities and differences in the approaches employed within past gas systems, compared to those found within present-day electricity systems. Examples such as the manifestation of peaks and troughs in demand over the timescales of weeks, months, and seasons, rather than the seconds, minutes and hours more commonly discussed in the electricity sector, reveal how different kinds of balancing issue can have major implications for the ways in which energy systems are configured. Studying how these issues manifest, and the ways in which they have historically been responded to, has value for understanding opportunities and challenges relating to balancing that may affect future electricity systems and may also have value for coming to terms with potential issues that could affect the balancing of other kinds of energy systems. 54

138 *Id.*
139 Boxall, *Improving Short Term Gas Demand Forecasting* (cf. note 111).
140 *Id.*
141 National Grid, "National Grid Emergency Operations" (Webinar, National Grid, 4th September, 2014).
142 *Id.*

55 2) Patterns of demand are affected by how energy is used and play a major role in how balancing is approached and how energy systems are organised. To date, discussions of 'flexibility' have primarily focused on the importance of the composition of energy supply for the balancing of energy systems, including how easily energy supplies can be stored, transported, or made to produce electricity. This paper has instead focused primarily upon the significance of the composition of energy demand for processes of balancing. A key finding is that how energy is used dramatically influences patterns of energy demand and can have major implications for how balancing is achieved. The paper has shown how changes in the dominant uses of gas across four time periods have influenced patterns of demand and have conditioned the kinds of balancing processes possible at different moments. With each change in gas usage, the organisation of the UK's gas systems has been shown to have undergone successive alterations.

56 More specifically, the paper has also documented how changes in the ways in which energy was used influenced the composition of demand across three dimensions: its timings, intensities and geographies. Each of these dimensions (which are described in more detail below) have been shown to have had consequences for how balancing could be approached, and for how energy systems were organised.

57 Timings. Different types of energy use influence the timings of energy demand in terms of the durations of demand peaks and troughs (seconds, minutes, days, weeks, months, seasons, years); their frequencies (daily, weekly, seasonal); and their regularities (here, daily vs. occasional). For instance, gaslighting introduced seasonal peaks in demand that endured over weeks and months, whereas the use of gas for cooking resulted in less seasonal demand patterns as well as multiple peaks within days and on Sunday afternoons and special occasions. These variations necessitated different balancing methods, from the duration of demand peaks influencing the kinds of storage that could be utilised, to the frequencies of peaks affecting the sizing of gas systems and their load factors.

Intensities. How energy is used also influences the intensities of energy demand. Issues concerning demand intensity have manifested in two ways in this paper: as forms of consistent increases in the volume of demand, and as forms of temporally or spatially inconsistent demand growth. In cases where demand grew consistently (such as during the early 1800s when demand for gaslight was burgeoning), widespread alterations to the sizing of gas networks were often required. This involved pipes and storage facilities being enlarged, new forms of infrastructure being developed for the production, transport and storage of gas, and larger workforces being recruited. In cases where growth in intensity was less spatially and temporally consistent, however, further issues often emerged, most commonly in relation to network load factors. At different times and in different ways, the UK's gas systems experienced pronounced differences in the intensities of peaks and troughs in demand over different timescales (hours, days, weeks, months/seasons) and across different locations (seaside areas, network peripheries). These differences could similarly create problems around the (in)adequate sizing of gas networks and the (in)abilities of networks to transport sufficient supplies of gas to locations of demand, but they also raised concerns around the cost of necessary measures for balancing, relative to the frequency and distribution of these peaks. Various strategies were consequently developed to try to balance gas networks whilst avoiding poor network load factors. 58

Geographies. The geographies of peaks and troughs in energy demand are affected by the ways in which energy is used. Since 1795, certain kinds of gas usage have proved more geographically variable than others. Whereas lighting loads were relatively consistent across town gas networks, cooking loads displayed greater geographical variance. For instance, particularly intense loads were often experienced during summer months in areas that served large numbers of seasonal caterers. As gas became 59 used for central heating, demand growth also occurred primarily within residential areas, often resulting in peaks in demand at network peripheries. Such spatially uneven demand patterns had implications for the organisation of the UK's gas systems, involving extensive infrastructural adjustments that could include the installation of gasworks and sites of gas production near to locations of demand; the use of booster stations; and the deployment of static gasholders close to residential areas. As the uses and users of gas multiplied; as gas networks became larger and increasingly interconnected; and as the UK's gas systems became further liberalised, issues with geographical demand variation also increased in scale and complexity, necessitating the emergence of demand forecasting as a routine aspect of the day-to-day balancing of gas networks.

60 These three qualities of energy demand (timings, intensities and geographies) are each dependent upon how energy is used and have implications for the balancing methods that are possible in a given moment. In the current context, this relationship could be particularly significant for thinking through attempts to pursue decarbonisation by shifting specific activities (in particular, transport and heating) off their reliance upon fossil fuels and onto electricity.[143,144] As electricity becomes used within different applications, it is highly likely that the timings, intensities and geographies of electricity demand will shift in ways that create new opportunities and challenges for balancing.

61 Moreover, beyond these qualities, the example of the UK's gas systems demonstrates the value of better understanding how energy demand is composed, including the ways in which it relates to different forms of energy use and what its implications are for processes of balancing. Furthering our understanding of this relationship will likely require studying how current electricity demand profiles relate to contemporary forms of electricity use but may also require further investigation of how forms of energy use within other kinds of energy systems in both the past and the present relate to patterns of demand.

3) The ways in which energy is used, and therefore the compositions of energy demand, are dynamic. As has been argued elsewhere,[145] current discussions of flexibility within the energy sector have been widely underpinned by assumptions that take the composition of demand to be static. The examples described in this paper testify to demand's constantly dynamic nature and its always-shifting relationships with patterns of energy supply. The examples described here speak of the changing ways in which people use energy, and of how these patterns of usage will likely continue to change in the future. The composition of energy demand (including its timings, intensities and geographies) will therefore also almost certainly change as a result. The examples described in this paper serve as a warning of the potential dangers of designing energy systems around these fixed understandings of demand. Across the history of the UK's gas networks, the infrastructures of gas provision have been repeatedly resized and reconfigured around new and emerging patterns of demand that have been characterised by different timings, intensities and geographies, and these alterations have often proved extensive and costly. 62

CONCLUSION

Current discussions of flexibility within the fields of energy provision, policy and research have centred around contemporary challenges concerning the balancing of fluctuating patterns of energy demand and supply. These discussions have overwhelmingly focused on present-day electricity systems and have been predominantly supply-oriented, attending to the consequences of material changes in the composition of energy supplies, such as the ease with which different forms of energy can be stored, transported or made to produce electricity, for processes of balancing. 63

143 BEIS, *Upgrading* (cf. note 2).
144 Centre for Research into Energy Demand Solutions (CREDS), *Shifting the focus: energy demand in a net-zero carbon UK* (Oxford: CREDS, 2019).
145 Stanley Blue, Elizabeth Shove, Peter Forman, "Conceptualising flexibility: Challenging representations of time and society in the energy sector", *Time and Society,* (Early access), 2020, https://doi.org/10.1177/0961463X20905479.

64 I have taken a different approach in this paper, instead studying the consequences of the shifting composition of energy demand for balancing the UK's gas networks across a 225-year timeframe. I have described four periods in which gas was predominantly used within different applications (gaslight, cooking, manufacture, central heating), and I have shown how the composition of demand, and the procedures employed to balance gas networks, changed as a result. In the process, I have demonstrated how issues relating to balancing fluctuations in demand and supply are not exclusive to electricity systems, nor are they limited to the present context. The historical study of gas systems reveals a plurality of moments in which tensions between patterns of gas demand and supply have emerged over time. These tensions have taken quite different forms: the timings, intensities and geographies of peaks and troughs in demand shifting in relation to how gas was predominantly used. I have also shown how these changing demand patterns were responded to via a variety of balancing strategies, many of which proved both extensive and costly. The longitudinal perspective provided by this account therefore serves as a reminder of the constant dynamism of energy demand and of the potential dangers of calibrating energy systems around fixed understandings of it.

However, looking beyond gas networks, the composition of energy demand, including what constitutes it, how and why it changes, and what opportunities and challenges for balancing it introduces, clearly requires further analysis. Indeed, understanding this relationship is important both for looking beyond the immediate balancing challenges facing decarbonising electricity networks, and also for understanding the longer-term consequences of the methods of balancing proposed in relation to these challenges. As this paper has shown, history can play a valuable role in coming to terms with this processes. Turning to examples from other energy systems in the past can help us to grasp the dynamism of the demand/supply relationship in ways that are often not possible through studies of the present, nor through projections of future patterns of consumption. 65

Bibliographie

Adam A., Vasey G.
"Evolution of the Modern Gas Fire", *Institution of Gas Engineers Journal*, vol. 10, 1970, 797-816.

Adam D.
"The Load Factor", *British Junior Gas Associations Joint Proceedings 1956-57*, vol. XXXX, 1957, 644-651.

Arapostathis Stathis
Natural Gas Network Development in the UK (1960-2010): Coping with Transitional Uncertainties and Uncertain Transitions (Cardiff: Low Carbon Research Institute, 2011). URL: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.645.6520&rep=rep1&type=pdf (accessed 21/10/20).

Barty-King Hugh
New Flame: How Gas Changed the Commercial, Domestic and Industrial Life of Britain Between 1813 and 1984 (Tavistock: Graphmitre Ltd, 1984).

Blue Stanley, Shove Elizabeth, Forman Peter
"Conceptualising flexibility: Challenging representations of time and society in the energy sector", *Time and Society*, (Early access), 2020, https://doi.org/10.1177/0961463X20905479.

Boxall Katie
"Improving Short Term Gas Demand Forecasting", *Gas International*, November 2015, 37-39.

British Gas
Gas Chronology: The Development of the British Gas Industry (London: British Gas, 1980).

Brooks E.
"Thermal Environment and Comfort in the Home: Progress, Procrastination, and Probable Trends", *Institution of Gas Engineers Journal*, vol.10, 1970, 523-537.

Bryant N.
"The Practical Handling of Interruptible Loads", *Institution of Gas Engineers Journal*, vol. 13, 1973, 317-324.

Buckley A.
"Gas Load Forecasting – A Marketing Contribution", *Institution of Gas Engineers Journal*, vol. 6, 1966, 169-181.

Burrell A., Fudge G.
"Domestic Space Heating by Gas", *British Junior Gas Associations Joint Proceedings 1956-1957*, vol XL, 1957, 132-149.

Centre for Research into Energy Demand Solutions (CREDS)
Shifting the focus: energy demand in a net-zero carbon UK (Oxford: CREDS, 2019).

Chrétien D.
Process for the Adjustment of the HHV in the LNG Plants (Amsterdam: 23rd World Gas Conference, 2006). URL: http://members.igu.org/html/wgc2006/pdf/paper/add10492.pdf (accessed 22/6/20).

Coe Arthur
The Science and Practice of Gas Supply Volume III, Including the Economics of Gas Supply (London: The British Commercial Gas Association, 1939).

Colburn Zerah
The Gasworks of London (London: Bucklersbury, 1865).

Copp Douglas
Gas Transmission and Distribution (London: Walter King Ltd, 1967).

Currie R.
"Selling Industrial Gas", *British Junior Gas Associations Joint Proceedings 1957-1958*, vol. XLI, 1958, 660-673.

Deans R.
"The Value of the Space Heating Load", *British Junior Gas Associations Joint Proceedings 1952-53*, vol. XXXVI, 1952, 861-875.

Department for Business, Energy and Industrial Strategy (BEIS)
Upgrading Our Energy System: Smart Systems and Flexibility Plan (London: BEIS, 2018).

Digest of UK Energy Statistics (DUKES): Natural Gas (London: BEIS, 2019). URL: https://www.gov.uk/government/statistics/natural-gas-chapter-4-digest-of-united-kingdom-energy-statistics-dukes (accessed 06/07/20).

Dolman Frederick
"Municipalities at Work", *The New Review*, vol.11, n°62, 1894, 74-86.

Edwards E.
"Gas Supplies for the North Thames Area", *Institution of Gas Engineers Journal*, vol. 6, 1966, 633-657.

Edwards K.
"The Requirements of Base Load Operation", *British Junior Gas Associations Joint Proceedings 1957-1958*, vol. XLI, 1957, 701-715.

Elliott Charles
The History of Natural Gas Conversion in Great Britain (Royston: Cambridge Information and Research Services Ltd., 1980).

Ellis J.
"Industrial Gas in Birmingham", *British Junior Gas Associations Joint Proceedings 1959-1960*, 689-720.

Emerson J., Roberts J.
"Summer Hot Water from Central Heating Boilers", *Institution of Gas Engineers Journal*, vol. 8, 1968, 364-384.

Stirling Everard
The History of the Gas Light and Coke Company 1812-1949 (London: A&C Publishers Ltd., 1992 [1949]).

Falkus M.
"The Early Development of the British Gas Industry, 1795-1815", *Economic History Review,* vol. 35, n° 2, 1982, 217-234.

Froggatt Antony, Quiggin Daniel
The Power of Flexibility: The Survival of Utilities During the Transformations of the Power Sector (London: Royal Institute of International Affairs, Chatham House, 2018).

Gatley Andy, Caraher Martin, Lang Tim
"A qualitative, cross cultural examination of attitudes and behaviour in relation to cooking habits in France and Britain", *Appetite,* vol.75, 2014, 71-81.

Giddings F.
"Gas Sets the Pace", *Institution of Gas Engineers Journal,* vol. 6, 1966, 377.

Grunewald Philip, Diakonova Marina
"Flexibility, Dynamism and Diversity in Energy Supply and Demand", *Energy Research and Social Science,* n°38, 2018, 58-66.

Hastings Charles
"British Commercial Gas Association", *The Gas Engineer's Magazine*, vol.29, n°441, 1913, 277-278.

Heslop D.
"Central Heating: Where from – where to? Some personal reflections 1958-1978 – Part 1", *Institution of Gas Engineers Journal,* vol. 20, 1980, 99-108.

Higgs A.
"Gas is Competitive", *British Junior Gas Associations Joint Proceedings 1956-57*, vol. XXXX, 1956, 456-486.

Holden R.
"Central Heating in Existing and New Property", *Institution of Gas Engineers Journal,* vol. 6, 1966, 628-629.

House of Lords European Union Committee
Brexit: Energy Security. 10th Report of Session 2017–2019 (London: House of Lords European Union Committee, HL Paper 63, 2018).

Howell W., Robertshaw G.
"Natural Gas and the Industrial Market", *Institution of Gas Engineers Journal,* vol. 8, 1968, 780-801.

Hughes S.
A Treatise on Gas-Works and the Practices of Manufacturing and Distributing Coal Gas (London: Lockwood & Company, 2010 [1871]).

Humboldt-Sexton Alexander
Producer Gas: A sketch of the properties, manufacture, and uses of gaseous fuel (Manchester: Scientific Publication Company, 1905).

Hutchinson K.
"The Future of the Gas Industry in Great Britain", *Institution of Gas Engineers Journal,* vol. 6, 1966, 537-552.

Institute of Gas Engineers and Managers (IGEM)
Gasholders: Recording an End of an Era (London: The British Library, 2014).

International Energy Agency (IEA)
Energy Transitions in G20 Countries: Energy Transitions Towards Cleaner, More Flexible, and Transparent Systems (Online: IEA, 2018). URL: https://webstore.iea.org/energy-transitions-in-g20-countries-energy-transitions-towards-cleaner-more-flexible-and-transparent-systems (accessed 22/6/20).

Johnson G., Taylor C.
"A Review of Post-War Domestic Gas Water Heating", *British Junior Gas Associations Joint Proceedings 1955-56*, vol. XXXIX, 1956, 131-166.

Jones R.
"The Chemical Control of Modern Base Load Works", *British Junior Gas Associations Joint Proceedings 1956-57*, vol. XXXX, 1956, 810-811.

Knights I., Allen J.
"High Speed Gas Networks", *Institution of Gas Engineers Journal,* vol. 6, 1965, 75-79.

Langford A.
"Methods for Reducing District Complaints", *British Junior Gas Associations Joint Proceedings 1933-34*, vol. XXIV, 1933, 283-288.

Langford K.
"Economics of Gas in Industry", *British Junior Gas Associations Joint Proceedings 1933-34*, vol. XXIV, 1933, 425-434.

Langford R.
"Planning Small Holder Stations to Reduce Operation and Maintenance Costs to a Minimum", *British Junior Gas Associations Joint Proceedings 1960-1961*, vol XLIII, 1961, 42-52.

Langford R., Wood P.
"Meeting the Storage Requirements within an Area Board", *Institution of Gas Engineers Journal,* vol. 13, 1973, 129-140.

Lawton E.
"The Manufacture of Gas from Oil: A General Review with Detailed Consideration of the 'Semet-Solvay' and 'Segas' Processes", *British Junior Gas Associations Joint Proceedings 1952-53*, vol. XXXVI, 1952, 644.

Le Fevre R.
Gas Distribution Engineering: The Principles for Students (London: Walter King Ltd., 1948).

Lloyd P.
"Industrial Gas Heating", *British Junior Gas Associations Joint Proceedings 1933-34*, vol. XXIV, 1933, 218-239.

Maiben J.
A statement of the advantages to be derived from the introduction of coal gas into factories and dwelling houses, as a substitute for the lights now in use: together with observations on the method of making and using it (Perth: John Maiben & Company, 1813).

Mintel
Changing British Diet – UK –May 2003 (London: Mintel International Group, 2003).

Moxley W.
"Peak Load Medium Pressure Distribution Systems", *British Junior Gas Associations Joint Proceedings 1956-1957*, vol. XL, 1956, 754-765.

Murray D.
"Industrial Gas in the Central Division", *British Junior Gas Associations Joint Proceedings 1960-1961*, vol XLIII, 1961, pp.387-390.

National Grid
National Grid Emergency Operations (Webinar, National Grid, 4th September 2014).

Physical Operations of the NTS and Winter Forecasting (Webinar: National Grid, 11th September 2014).

Nestle Family Monitor (NFM)
Eating and Today's Lifestyle (London: Carried out by MORI on behalf of Nestle UK, 2001).

Oates J.
"Presidential Address, Manchester Association General Meeting, 17th October 1953", *British Junior Gas Associations Joint Proceedings 1953-54*, vol. XXXVII, 1953, 261-270.

Parker A.
"The Manufacture of Blue Water Gas", *Nature,* vol.115, 1925, 501–502.

Peebles Malcolm
Evolution of the Gas Industry (New York & London: New York University Press, 1980).

Pennell Sara
The Birth of the English Kitchen, 1600-1850 (London: Bloomsbury, 2016).

Popplewell Frank
"Seasonal Fluctuations in Employment in the Gas Industry", *Journal of the Royal Statistical Society,* vol.74, n°7, 1911, 693-754.

Pratt A., Johnson E.
"Storage", *Institution of Gas Engineers Journal,* vol. 7, 1967, 603-620.

Robinson H.
"Radiant Heating – Past, Present and Future", *British Junior Gas Associations Joint Proceedings 1955-56*, vol. XXXIX. 1956, 720-724.

Roger W.
"What's in a Peak Day? – Alternative Uses of the Planning Model", *Gas Engineering and Management: Journal of the Institution of Gas Engineers,* July/August, 1984, 269-281.

Sanders D., Hart A., Ravishankar M., Brunert J.
An Analysis of Electricity System Flexibility for Great Britain (London: Carbon Trust/Imperial College, 2016).

Schivelbusch Wolfgang
Disenchanted Night: The Industrialization of Light in the Nineteenth Century (California: California University Press, 1983).

Smith N.
Gas Manufacture and Utilization (London: The British Gas Council, 1945).

Stern Jonathan
"The British Gas market 10 years after privatisation: A model or a warning for the rest of Europe?", *Energy Policy,* vol. 25, n°4, 1997, 387-392.

Stock John
"Carl Auer von Welsbach and the Development of Incandescent Gas Lighting", *Journal of Chemical Education,* vol. 68, n°10, 1991, 801-803.

Stretton J.
"The Development of Industrial Gas Sales in North Wales", *British Junior Gas Associations Joint Proceedings 1960-1961*, vol. XLIII, 1960, 473-478.

Summersgill K.
"Some Aspects of Grid Interlinkage", *British Junior Gas Associations Joint Proceedings 1953-54*, vol. XXXVII, 1954, 365-385.

Terrace J.
Terrace's Notebook for Gas Engineers and Students (London: Ernest Benn Ltd, 1948).

Thomas G.
"Factors Associated with and Influencing the Growth of the Industrial Gas Load in East Anglia", *Institution of Gas Engineers Journal,* vol. 6, 1966, 772-776.

Tomory Leslie
"Building the First Gas Network, 1812—1820", *Technology and Culture,* vol. 52, n°1, 2011, 75-102.

Tomory Leslie
"Fostering a new industry in the Industrial Revolution: Boulton & Watt and gaslight 1800–1812", *The British Journal for the History of Science,* vol. 46, n°2, 2013, 199-229.

UK Government
Liverpool (Corporation) Electric Lighting Act (London: UK Government, 1879).

Electric Lighting Act (London: UK Government, 1882).

Gas (Standard of Calorific Power) Act (London: UK Government, 1916).

Gas Regulation Act (London: UK Government, 1920).

Gas Act (London: UK Government, 1948).

Ward E.
Gasmaking (London: The British Petroleum Company Ltd, 1959).

Warde Alan, Yates Luke
"Understanding Eating Events: Snacks and Meal Patterns in Great Britain", *Food, Culture & Society,* vol. 20, n°1, 2017, 15-36.

Wilson John
Lighting the Town: A Study of Management in the North West Gas Industry 1805-1880 (London: Paul Chapman Publishing Ltd, 1991).

Windiate G., Craddock E.
"The Application of Town Gas to Industrial Heating Problems", *British Junior Gas Associations Joint Proceedings 1934-35*, vol. XXV, 1934, 110-113.

Yeaman A.
"Carbonisation on Base Load Works", *British Junior Gas Associations Joint Proceedings 1957-58,* vol. XLI, 1957, 834-854.