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AUTEUR
Simone Abram
Department of Anthropology, Durham University.
simone.abram@durham.ac.uk orcid.org/0000-0002-8063-3144
Antti Silvast
Department of Interdisciplinary Studies of Culture, Norwegian University of Science and Technology.
antti.silvast@ntnu.no orcid.org/0000-0002-1026-6529

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Flexibility of real-time energy distribution: the changing practices of energy control rooms

Résumé
This paper examines the linked concepts of flexibility and control, focusing on how these are enacted in the operation of control rooms in Distribution Network Organisations. We discuss the limits to flexibility, and the kinds of flexibility that are at stake in distribution network control of gas and electricity. We do not present a general history of flexibility in UK energy system control rooms, but we show how the legacy of past ideas and practices of energy distribution control feed into current control operations, and how they shape flexibilities in control systems. The article examines the kinds of flexibility demanded of control room engineers in the face of imperfect systems and unpredictable faults.

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Plan de l'article

INTRODUCTION

1 In the context of energy systems, the notion of flexibility is generally associated with the need to match supply with demand. If either is fixed, it follows that the other must be flexible. From this point of view flexibility and control are not opposites but two ways of conceptualising the means by which a system is managed. In this paper, however, the focus is not on the work of maintaining a balance between supply and demand. Rather than identifying flexibility in the organisation of energy demand or in the ability to produce supply at short notice, we look directly at the process of controlling this relationship, asking whether there is room for flexibility in how this work is configured and organised.

2 We focus specifically on the function and emergence of 'control rooms' in the energy distribution networks (gas and electricity), drawing on a qualitative study based in the North East of England. Once we began to look closely at control room operations, it became clear that despite the extremely tight regulation of what goes on in control rooms, the skill, intuition, creativity and flexibility of the control room operators, so-called 'shift engineers' and 'shift managers' is crucial.

3 In this paper, we look at the role of distribution-level control rooms in the DNOs (Distribution Network Organisations – currently being reframed as Distribution System Organisations or DSOs), asking what flexibility staff have to operate in new ways, what the limits are to their flexibility, and what kinds of flexibility are at stake. The work undertaken in these control rooms is primarily grid management and maintenance, including fault-response and the remote supervision of on-site repairs by sub-contractors and contracted staff. Load-balancing is managed at the Transmission Network level (in the UK, by National Grid) for both gas and electricity networks. Distribution network control rooms play a crucial role, however, in maintaining the smooth operation of the distribution network, linking transmission to supply, managing safety and security, and supervising the planning and implementation of repairs and installation of new equipment. Although operations are closely regulated by the national regulator (OFGEM), control room staff are highly trained to use their own experience and intelligence to manage both foreseen and unforeseen situations. Hence, we argue that despite the tight security and strict procedures, flexibility and creativity are required of the staff.

4 We do not present a general history of flexibility in UK energy system control rooms, but we do draw on historical documentation in explaining what prove to be key features of control room 'work'. In prioritising a contemporary view, we consider how the legacy of past ideas and practices of energy distribution control feed into current practices, and how the types of flexibility encountered in control systems emerge out of 'legacy assets' as well as conventions and changing traditions of practice.

FLEXIBILITY IN ENERGY SYSTEMS AND CONTROL ROOMS

5 Any study of contemporary energy systems in the UK inevitably has to address the jumble of old and new 'assets', or items of equipment that constitute the energy infrastructure that has accrued over time. Far from being an ideal rational system, energy distribution relies on layers of infrastructure that date back many decades. These include complex material and regulatory infrastructures, alongside equipment that may have been installed up to 70 years ago, staff of various degrees of longevity in different organisations, and enduring conceptual understandings and common principles. In this article, we report on a short research project looking at the degree and kinds of flexibility this leaves for control room operators (or engineers) in two distribution control rooms in the electricity and gas sectors in the UK.

6 Using ethnographic methods (primarily participant-observation and in-depth interviews), we were able to discuss these different types of legacy with control room engineers, and to

reflect on the lived memory of change and continuity over recent decades. Hence, this paper takes a distinctive approach to energy history, using anthropological and historiographic methods to consider how past socio-material practices live on in the present in the form of material 'assets' or equipment, infrastructures, modes of doing, and memories of changing practices. We discuss the workings of distribution network control rooms to show where flexibility is found and how it is changing over time.

7 The kind of flexibility we consider here is more operational and finer grained than that which features in normative abstracted discourses of flexibility. Blue *et al*[1] suggest that energy providers, policy makers, and some researchers see flexibility as a technical capacity of the whole energy system, or as a commodity that can be traded or managed through specialized techniques such as demand-side management. Whilst some social researchers treat flexibility as a function of the technical infrastructure,[2,3,4] others take a broader view, conceptualising it as "an emergent outcome of the historical development of constellations of practices that make up social life".[5]

8 In this paper we complement these accounts by homing in on the 'room for manoeuvre' in distribution control rooms as a means of exploring the possibilities for new forms of inter-sector cooperation. We therefore focus on how distribution control is conceptualised, managed and operated in these sites and what this means for shift engineers in their day to day work in control rooms. In other words, we take a more colloquial approach to flexibility as an idea, asking whether and where there is room for creativity or innovation in control room practices, rather than in the management of supply and demand. We could reiterate here also that we are not taking a normative approach to improving the operation of control rooms, but making an empirical enquiry into infrastructure practices in a contemporary but historicised context.

Control room[6] operations themselves are relatively rigid. Routine and procedure tied to lengthy and rigorous training programmes are the primary methods used to ensure that safe and reliable operations are enacted in the control room practices we discuss below. Each routine is in itself backed up by a folder of specifications, rooted in regulatory codes and licence conditions. A closer look at distribution control rooms helps to illustrate how tightly-regulated control room practices are, where the interstices are that allow for different kinds of flexibility, as well as how restricted the discussion of flexibility has tended to be in the energy literature so far. Our findings contribute to an understanding of the changing politics of flexibility in anticipation of low-carbon energy systems which may be anticipated to require some integration of control between different energy 'vectors' such as gas and electricity systems. 9

1 Stanley Blue, Elizabeth, Shove, Peter Forman, "Conceptualising flexibility: Challenging representations of time and society in the energy sector", *Time & Society*, vol. 29, n° 4, 2020, 923-944.

2 Elizabeth Shove, Noel Cass, "Time, Practices and Energy Demand: implications for flexibility. Insights across DEMAND", 01/05/2018. Url: **http://www.demand.ac.uk/wp-content/uploads/2018/06/Time-practices-and-energy-demand-final.pdf** (accessed 07/08/2020).

3 Jacopo Torriti, "Flexibility", *in* Jenny Rinkinen, Elizabeth Shove, Jacopo Torriti (eds.), *Energy Fables: Challenging Ideas in the Energy Sector* (London: Routledge, 2019).

4 Gareth Powells, Michael J. Fell, "Flexibility capital and flexibility justice in smart energy systems", *Energy Research & Social Science*, n° 56, 2019, 56-59.

5 Blue et al "Conceptualising Flexibility" 12 (cf. note 1).

6 Henceforth we use the term 'control room' to imply distribution-network system control rooms

MATERIALS AND METHODS

10 Empirical studies of infrastructure control rooms often use on-site interviews and observational field research methods,[7,8,9,10,11,12] while workplace studies and ethnomethodological research often draw on video-based studies of interactions in control rooms and conversations recorded in those videos.[13] Our project used observational and interview methods, including in-depth interviews and participant-observation in the North of England in 2019, in an electricity distribution and a gas distribution network company respectively. In total, 6 gas control room operators and 12 electricity control room operators have been interviewed and observed, and we conducted over 30 hours of participant observation in the respective control rooms.[14] Given the security issues around system control operations in critical infrastructure such as energy, we must necessarily leave many details out, and occasionally blur the information we present, out of respect for the safety requirements in the system. We hope that this leaves sufficient detail to satisfy the reader.

In addition the paper draws on selected his- 11
torical documents, including those published in trade journals, technical academic journals, oral histories of energy-industry engineers, and secondary historical sources. These allowed us to incorporate perspectives on the historical emergence of control in energy systems and to show how flexibilities emerge as part of supply-demand relationships at different times.[15] The views expressed in these secondary articles on hierarchies of control, systems theories, and early calculative techniques of energy systems situate present flexibilities as part of longer term processes that continue to influence the life-cycles of infrastructures, and thus the strategies enacted in the control rooms of the present.

THE PRACTICES AND HISTORIES OF CONTROL ROOMS IN GAS AND ELECTRICITY DISTRIBUTION

Histories of control rooms in gas and electricity distribution

The character of flexibility in control room oper- 12
ations today is certainly shaped by the development of control-rooms as a means of operation within the development of energy systems more generally. In this section we briefly summarise how control rooms emerged in the gas and electrical systems to offer historical context for the study we go on to describe.

There are relatively few documented histories 13
of energy system control in the UK although there are accounts of energy supply and system

7 Lucy Suchman, “Centers of coordination: A case and some themes”, *in* Lauren B. Resnick, Roger Säljö, Clotilde Pontecorvo, Barbara Burge (eds.), *Discourse, Tools, and Reasoning: Essays on Situated Cognition* (Berglin: Springer-Verlag, 1997), 41-62.

8 Mark de Bruijne, Michel van Eeten, “Systems that Should Have Failed: Critical Infrastructure Protection in an Institutionally Fragmented Environment”, *Journal of Contingencies and Crisis Management*, vol. 15, n° 1, 2007, 18-29.

9 Emery Roe, Paul Schulman, *High Reliability Management: Operating on the Edge* (Stanford: Stanford Business Books, 2008).

10 Andrés Luque-Ayala, Simon Marvin, “The Maintenance of Urban Circulation: An Operational Logic of Infrastructural Control”, *Environment and Planning D: Society and Space*, vol. 34, n° 6, 2016, 191-208.

11 Antti Silvast, *Making Electricity Resilient: Risk and Security in a Liberalized Infrastructure* (London: Routledge, 2017).

12 Antti Silvast, “Co-constituting supply and demand: managing electricity in two neighbouring control rooms”, *in* Elizabeth, Shove, Frank Trentmann (eds.), *Infrastructures in practice: the evolution of demand in networked societies* (London: Routledge, 2018), 171-183.

13 Christian Heath, Paul Luff, *Technology in Action* (Cambridge: Cambridge University Press, 2000).

14 The research was carried out under the auspices of the National Centre for Energy Systems Integration (CESI) in a flex-fund project that sought to study the implications of energy systems integration on control room practices and regulations. The project aimed to open up questions about the potential and challenges for control room integration, in response to anticipated changes in energy system management.

15 We are particularly grateful to Peter Forman and Julie Cohn for their advice and guidance.

control from the US context.[16,17,18,19] However, there is a wealth of technical and historical literature on gas systems, often written by gas engineers themselves,[20,21,22] with some attention to regional systems. In relation to electrical systems, most attention has been devoted to research on grid-scale transmission and control, with far less attention given to the distribution systems that are the focus of this paper. Finally, while extensive histories of early electrification are available for the UK,[23] Germany, and the United States,[24] these histories do not cover the late 20th century or early 21st century. In this paper we draw on this range of sources in describing how control rooms emerged in electricity and gas distribution, why, and what issues they created.

14 What is particularly striking in accounts of the development of system control in the UK (and elsewhere) is the significance of automation and digitisation. In the electricity industry, digitisation has been central in a way that Slayton derides as "digital utopianism" and traces to the deregulation of the energy sector in the 1980s and the 1990s.[25] However, debates about automation and remote-control go back to almost the start of the development of grids. Gas networks were monitored from centralised control rooms (or governor houses) from the 1860s,[26] while emerging grids, such as the 'Sheffield Grid' had control centres from the 1930s.[27] Eight area gas boards were established in the 1960s, which progressively set up grid controls, with shift control officers appointed to a centralised (national) grid control function in 1967. Regional grid control had been set up for the North East of England in 1955, including responsibility for 'co-ordinating day to day operations of all gas production plant, liaison with the Coal Board (for coke oven gas) and with other private supplies'.[28] After conversion to natural gas, control was consolidated and computerised, with telemetry control rooms established by 1981 across the North of England, and updated systems commissioned from 1991 onwards.[29] In this context, controlling gas included the management of pressure and the content of holders, at first through networks of sub-control rooms, and latterly through the regional boards' unitary control rooms. Gas control subsequently evolved to mirror electrical control operations, with centralised transmission control rooms for high voltage/high pressure transmission, and regional distribution control rooms operated by the 8 boards (later companies). Francis notes the introduction of remote-control valves from 1973, and remote-control compressors from 1981.

In the electrical system, analogue machines of the 1950s and earlier provided scale models of the electricity network that were used by electricity systems operators,[30] but by the 1920s automatic frequency control had been introduced in order to keep the alternating current 15

16 Eg. Aristotle Tympas, "Perpetually Laborious: Computing Electric Power Transmission Before the Electronic Computer", *International Review of Social History* vol. 48, supplement, 2003, 73-95.

17 Rebecca Slayton, "Efficient, Secure, Green: Digital Utopianism and the Challenge of Making the Electrical Grid 'Smart'", *Information & Culture*, vol. 48, n° 4, 2013, 448-478.

18 Julie Cohn, "'The old was analogue. The new was digital': Transitions from the Analog to the Digital Domain in Electric Power Systems", *IEEE Annals of the History of Computing*, vol. 37, n° 3, 2015, 32-43.

19 Julie Cohn, *The Grid: Biography of an American Technology* (Cambridge, MA, MIT Press, 2017).

20 E.g. F. S. Charnley, *Some Aspects of Distribution Control as Applied to Interlinked Undertakings, Meeting: 3 November 1951* (Rotherham: Yorkshire Association, 1951).

21 W. Moorcroft, *The Design and Operation of an Automatic Distribution Centre, Meeting: 20 January 1960* (Manchester: Manchester Association).

22 R. F. Francis, *Grid Control – Past, present and future. Presented to Institution of Gas Engineers, Wales District Session 1991/1992* (Kegworth: Institution of Gas Engineers, 1991).

23 L. Hannah, *Electricity before nationalisation: a study of the development of the electricity supply industry in Britain to 1948* (Baltimore: Johns Hopkins University Press, 1979).

24 Thomas P. Hughes, *Networks of power: electrification in western society, 1880–1930* (Baltimore: Johns Hopkins University Press, 1983).

25 Rebecca Slayton, "Efficient, Secure, Green" (cf. note 17)

26 Francis, *Grid Control* (cf. note 22)

27 Ibid., 8

28 Ibid., unnumbered appendix

29 Ibid.

30 Julie Cohn, "'The old was analogue. The new was digital'" (cf. note 20) on the grid as close as possible to 50Hz. If we associate "computing" with its definition as performing calculations, there was already an infrastructure of human calculators and electric network analysers in the late 19th century, introduced to help calculate 'processes' of electrification.[31] The emergence of digital technologies and computers in the 1950s increased speed, accuracy, and capacity to address complexity. As Cohn[32] suggests: "Digital computers ... processed larger quantities of data at a faster speed and produced more accurate results. ... They could handle almost any degree of complexity and produced logical decisions."

16 In the electricity sector, centralised computerised control was primarily developed in relation to transmission. In the USA, centralisation was framed in relation to security, especially following the major blackouts of 1965. According to Dy Liacco,[33,34] an electrical engineer referred to as the father of modern energy control rooms, computer software should be imagined as a means to embed security and remove danger and risk from electricity: "Security functions are now incorporated into computer programs to deal with operating conditions as well as with disturbances that could lead to equipment overloads, voltage degradation, frequency decay, system instability, service interruption, or the ultimate catastrophe of a system shutdown".[35] The UK's Central Electricity Generating Board (CEGB) also developed a computer simulation of the security of the national power grid in 1965,[36] with both US, UK and European engineers comparing notes and influencing one another's ideas; Jack Casazza claimed to have been inspired by European ideas for a project to computerise 'total system control' using a 'security assessor' when developing system control in New Jersey following a blackout in Philadelphia.[37]

What emerged from this gradual accretion of control operations was a relatively standardised form of centralised control-room that we discuss below. 17

What is a control room?

In the most general terms, control rooms can be understood as the locus of management for distributed infrastructure. Roe and Schulman, for example, note that, 'control rooms across many infrastructures share the same overarching aim: managing a critical service reliably and safely, in real-time, given their system definitions and the specifics of their governing reliability standards.'.[38] 18

In focusing on control rooms, our study is reinforced by decades of theoretical interests developed in workplace studies and organisational studies based on the well-known idea that systems with interactive complexity and tight coupling are prone to unanticipated failures.[39] While the notion of distributed infrastructures provides a compelling example of such systems,[40] studies of vital infrastructures in general and electricity grids in particular have rarely found that these anticipated failures actually manifest.[41,42] Control room workers are faced with complexity, yet develop vigilance and concentration by their working habits, skills, and a culture 19

31 Aristotle Tympas, "Perpetually Laborious" (cf. note 18)
32 Ibid., 37.
33 Tomas Dy Liacco, "Real-time computer control of power systems", *Proceedings of the IEEE,* vol. 62, n° 7, 1974, 884-891.
34 Tomas Dy Liacco, "System Security: The Computer's Role", *IEEE Spectrum*, vol. 15, n° 6, 1978, 43-50.
35 Ibid., 43.
36 Julie Cohn, *The Grid"* (cf. note 19., 243)
37 Loren J. Butler, Jack Casazza, "An oral history conducted in 1994, IEEE History Center, Hoboken, NJ, USA", 01/02/1994. Url: **https://ethw.org/Oral-History:Jack_Casazza** (accessed 07/08/2020).
38 Emery Roe, Paul Schulman, "A reliability & risk framework for the assessment and management of system risks in critical infrastructures with central control rooms", *Safety Science,* vol. 110, 2018, 80-88, 2.
39 Charles Perrow, *Normal Accidents: Living with High Risk Technologies* (Princeton: Princeton University Press, 1984/1999).
40 See Antti Silvast, Ilan Kelman, "Is the Normal Accidents Perspective Falsifiable?", *Disaster Prevention and Management*, vol. 22, n° 1, 2013, 7-16.
41 Mark de Bruijne, Michel van Eeten, "Systems that Should Have Failed." (cf. note 10)
42 Emery Roe, Paul Schulman, *High Reliability Management*" (cf. note 11)

of safety. The literature developing these arguments about control rooms (including space, aviation, nuclear, and military applications), known as high reliability theory,[43] argues that organisations can achieve high reliability in spite of complexity and coupling. Conversely, systems failures can also be due to organisational culture and management rather than being just traits of systems.[44] This leaves room for asking where the flexibility lies within such systems, but the question is not at the forefront of this literature.

20 In parallel, Science and Technology Studies, and particularly in the tradition of ANT, have attended to a broad range of centres of power and control that are understood as political as well as physical. Law's work on 'action at a distance', for example, shows how centres for navigation acted also as political mechanisms to control distant envoys and empires.[45] It is possible to see that system control centres through their management and development of nation-wide infrastructures also have a nationalising role, embedding state-provided or state-regulated services across the nation-state, and also negotiating terms between nation-states (in the case of national grids, through interconnectors, for example). However, perhaps more relevant to our study of regional distribution network control is the notion launched by Latour[46] of 'centres of calculation', where various data including diagrams, maps, logs, and statistics are accumulated and transformed into broadly accepted knowledge. Both indicate that centres of control exist only in relation to distant actions, and rely on technologies of knowledge that transport information about the world to the calculative centre, which transforms it into knowledge as the basis for infrastructures to be set out again for the purpose of action at a distance.

What constitutes the actual 'room' in which control is exercised is therefore debateable, and much of the preparatory work for our field-research consisted of identifying what was meant by 'control room' operations, and which physical location we were actually interested in observing, suggesting to us that the very definition of 'control room' contains a greater degree of flexibility than we had anticipated. On the one hand, there is the physical room in which remote-information system monitors are situated, and where shift engineers and shift managers undertake the tasks of control room operation. But the physical room with its participants and their activities is intrinsically tied into systems created and managed in other arenas. There is a layer of control room planning and management that usually happens outside the physical control room itself, for example. This 'support' may include the management of the communications software and its configuration, detailed planning and scheduling of site-based routine maintenance or repair works (i.e. 'out there' on the grid infrastructure), liaising with outside agencies and sub-contractors, organising the shifts of staff in the control room, and so on. 21

Occasionally a support engineer (that is someone responsible for managing the kinds of support outlined above) may sit in the room to monitor the operation of the system and observe where improvements need to be introduced, but in the UK transmission and distribution network world that we have observed, control operations and support are generally seen as separate, if linked functions. The room in which control functions are enacted on a day-to-day basis has thus achieved a degree of fetishization in the energy industries. By this we indicate a degree of reverence that is created by the heightened security around control room access and operation. The apotheosis of this is the centralised transmission-system control rooms of the National Grid, with glass viewing-platforms for visitors, and 22

43 Gene Rochlin, Todd La Porte, Karlene H. Roberts. "The self-designing high-reliability organization: Aircraft carrier flight operations at sea", *Naval War College Review* vol. 40, n° 4, 1987, 76-92.

44 E.g., Diane Vaughan, "Theorizing disaster: Analogy, historical ethnography, and the Challenger accident", *Ethnography* vol. 5, n° 3, 2004, 315-347.

45 John Law, "On the Methods of Long Distance Control: Vessels, Navigation, and the Portuguese Route to India", *in* John Law (ed.), *Power, Action and Belief: A New Sociology of Knowledge?* (London: Routledge, 1986), 234-263.

46 Bruno Latour, *Science in action: How to follow scientists and engineers through society* (Harvard: Harvard University Press, 1987), 232.

the supposedly secret location of the emergency backup Control Room to be used in cases of extreme national emergency. While the degree of reverence is rather less pronounced at the distribution level, all staff know that control room engineers should not be unduly disturbed, and that office sociality would always be subservient to disturb control room operations (as we detail below). Even our request for access to observe the control room operations for research purposes went through several rounds of approvals and was allowed on condition that we kept quiet and out of the way and did not disturb operators.[47] We were also asked, in one instance, not to indicate to our taxi driver the function of the building we were travelling to.

23 A control room is, by definition, linked through communication systems to the broader infrastructure, whether that is by the data system communications, emails, telephone lines or, (perhaps surprisingly still) fax machines, such that the tentacles of control reach in and out of the room where the shift engineers operate. The equipment and activities in the control room itself are subject to a suite of regulatory codes, legal strictures and safety routines, as well as management procedures and protocols. As control room staff use communications equipment such as telephones, their reach extends to remote sites through communication with site-engineers.

Taking these layers into account, even based on a narrow definition, the control room can be conceived to include:

- The physical space (the control room).
- The people who work within that physical space (operators).
- Physical equipment within that physical space, which is connected to distributed monitoring and control systems (control and monitoring systems).
- Tools and systems for analysing and forecasting data from monitoring systems and recommending actions.
- A framework of procedures, rules, guidelines, protocols.
- Connections and communications to external infrastructures.
- A support system of planning and operation agents.
- A broader framework of commercial operations in which the company operates.

A control room may therefore be conceptualised as a physical space housing control equipment and operators, but is intimately connected to diverse and distant elements of infrastructure by physical, conceptual and governmental means. It is certainly a 'centre of calculation', even if much of the literally calculative action is nowadays managed through digital systems leaving shift engineers to organise off-site responses to distant maintenance issues, faults and repairs. Changes to the calculative system itself (ie the workings behind the digitised systems) are undertaken by separate groups of support engineers usually located outside the core control room (as noted above). 24

Such generic descriptions of control rooms leave out the specific histories and politics of how they have been set up in different periods and contexts. The energy sector includes various kinds of control rooms, from large scale power-station operations to distribution and transmission networks. These serve different purposes under the general engineering rubric of 'control'. For example, DNOs are responsible for the distribution of energy from the transmission system to the supply level, but while they are required to despatch energy to meet demand within the constraints of the distribution network, their primary role is to maintain the system in working order, and oversee outages and repairs on the ground from the control room. Procedures, rules, codes and guidelines are intended to reflect the requirement to prioritise safety and reliability, but they also relate to the commercial and regulatory framework within which the critical service operates. 25

47 Indeed, we were pleasantly surprised by how much the operators were actually prepared to converse with us in practice and talk us through their activities, although we were told clearly when that was not possible, as engineers responded to calls and so forth.

26 The control of energy in terms of distribution (moving it from here to there) is separated from the forms of control involved in the commercial 'arm' of the organisations at the practical level. Distribution control operators inform us that they have little contact with the company's commercial operations, which are removed to another site (so much so that they appeared to know little, if anything, about it). In other words, control room operation at DNOs is strictly demarcated around safety and distanced from commercial imperatives. Control room operators are not required to use any creativity or flexibility in relation to the commercial interests of the company, since budgeting and accounting for repairs and maintenance is managed in another area (eg in 'support' or planning operations), although shift engineers in some companies are taken off the front line every few years to work on the support side, where they have an opportunity to use their experience to reflect more strategically. Even so, one shift manager who had come up with a scheme to improve the efficiency of maintenance schedules was actively rebuffed by the organisation's management.

What happens in the control rooms we visited?

27 The control rooms we visited shared certain key features. Each was housed in an innocuous-looking office block, and consisted of a suite of office tables and computer monitors. On the walls were TV screens showing weather forecasts, and in the electricity control rooms, a wall monitor displayed the frequency of the grid in real-time. Control engineers claimed that this was largely ignored, being present only to fulfil regulatory requirements, since alerts about system frequency would be picked up through other monitoring systems without the need for the wall monitor. The weather monitor they used only to check if significant electrical storms might be approaching, or to be alert for potential faults. By contrast in the gas control room, weather information fed into daily forecasts for day-ahead demand.

28 Each desk had two or three monitors and a telephone, while the electricity control room desks also had head-pieces for the telephones, which could be doubled and shared. Operators have printed lists to work with, as well as an operating system that gives them multiple views of the external energy infrastructure network. The remote system is known as SCADA which stands for Supervisory Control And Data Acquisition, a commonly used system in various applications. The system works at various scales, so that operators can see the whole network, or zoom in as far as individual 'assets' or pieces of equipment on a schematic basis (ie through symbolic diagrams, not via satellite imagery for example). The system shows a selection of conditions of local equipment – for gas they show pressures and valve positions in various pumps and treatment assets, while the electricity system provides details of voltages, currents, switch positions, etc.. This information remains partial, only indicating asset ratings or certain faults. The degree of remote control is equally partial, with some transformers or circuit breakers operated from the control room while others require manual operation on site. Most of the operations happening in the control room could be better described as communication management rather than remote operations. Control room engineers have oversight of the whole system, and take responsibility for one area during their shift, which might extend to a whole geographic county or a larger region. Within that area, they will be furnished (by the planning and support office) with a list of repairs and maintenance activities that are to be undertaken during the shift, and they will respond to faults or errors that crop up. These might appear on an 'alert' screen as unexpected conditions that require attention, or they may be routed through the customer service centre if members of the public call in to report faults or outages, or occasionally they might be telephoned in by site engineers.

Each control room housed only a very small number of engineers, between 4 and 6, with each taking responsibility for a large area of the regional network. In response to either scheduled work or fault alerts, the shift engineers speak to (mostly sub-contracted) on-site engineers to ensure that 29 the site operations are carried out safely and to the required specifications. In both gas and electricity control rooms, the engineers follow a protocol to ensure that communications are fully understood, with a particularly strict protocol of call and repeat observed in the electricity control room. Control room engineers read step-by-step from a script prepared by the support engineers, requiring the on-site engineers to repeat back word for word, to ensure that what is recorded in the control room matches what is happening on the ground, so that both sides know whether and where currents may be flowing, to protect workers and assets.

30 This method, well-established at the time of our study, enables the control room engineers to extend their surveillance of the external network beyond the digital information systems that feed their monitors, effectively giving them contact with 'eyes on the ground'. Hence when a field engineer reports that a breaker is closed while it is showing on the SCADA system as open, they can discuss why this might be, where the fault lies and what the remedy might be. For example, the field engineer might recognise this fault from a previous occasion, and know that a worn part allows this particular breaker to close itself, and the instruction to close the breaker can be aborted. This will then be logged on the information system as a known fault, either to be recognised next time, or to be fed into a schedule of repairs to be corrected in the future. In detail the 'history' of the system is built up by accretion of details like these. Control room engineers and, indeed, engineers on the ground, use their own knowledge and experience to complement the information from the digital information systems they use, and can operate these systems flexibly, in that sense, based on their knowledge of its shortcomings and limitations.

31 In both control rooms, a general tenor of relaxed but alert operation is noticeable. There is little chit-chat, although at very quiet times the engineers may have light-hearted conversations. Instilled into them during a long period of training is the imperative of professional safety management, and the recognition that other people's safety – people's lives, indeed - relies on their professional conduct. Outside the control room itself, such as in the office where the support staff work, there might be a social gathering to send off a member of staff who is leaving, with cakes and drinks being shared but this would not happen in the control room. In fact, neither control room event instituted formal breaks, with staff informally making each other cups of tea and coffee, covering each other's desk for comfort breaks, and either bringing their own packed lunches or ordering in food rather than taking time out, since that would require an additional layer of formal staffing that neither organisation offered. Since the control rooms were organised to respond to unexpected events as well as manage routine maintenance, breaks were flexible too, fitting into moments of quiet and being disrupted if any kind of emergency cropped up. Both control rooms had trainee staff on hand who could cover for less-regulated tasks within their level of qualification, thus also learning to be flexible in their approach to the work.

Attention is always primarily on the SCADA system, the schedules of operations, and on any emerging conditions that may require attention. A pervasive atmosphere of calm, focused attentiveness is almost palpable, reinforcing the sense that things are 'under control'. In other words, the control room engineers exert a degree of emotional control that minimises external distractions (e.g. from interpersonal frictions). This helps them keep focused on the tasks at hand while controlling the potential stress of dealing with multiple and sometimes unpredictable or complex fault responses that, at the same time, require them to think flexibly and creatively to solve problems efficiently and, above all, safely. 32

Specificities of the gas and electricity control rooms

While much of the control room operation was similar for each network, there were a few notable differences that shape the degree of flexibility available to the engineers. Gas control engineers monitor pipe pressures, check on the condition of gas being fed into the system from biogas generators and on particular requests 33 for supply that might have come in from major consumers, as well as emerging faults or routine maintenance schedules, while watching weather forecasts that might alert them to possible changes in demand. Electricity control engineers also watch the weather forecasts, although only to check for electrical storms that might cause faults.[48] They also have a grid frequency monitor in the room to comply with regulations, but tell us that if the frequency were to go awry, they would probably know about it already from other indicators, as noted above. In both cases, reports of faults that come in from members of the public are routed through a call centre, which triages the calls and forwards details of any significant problems that must be dealt with.

34 Gas control room engineers calculate day-ahead forecasts at five points during the day, which are then sent to the transmission network operators to help plan the next day's supply, a duty that is not undertaken in the electricity control room. The gas control room engineers use modelling software to help them match expected demand patterns to historical patterns, aggregated for comparison, but they also combine this with experience, giving them a sense of the likelihood of particular patterns arising, based on a broad set of contextual factors (including patterns of changing weather, season, day of the week, public events, and so on). Forecasting is a process that clearly builds on past patterns and trends. Completely unprecedented events cannot be forecast, but known upcoming events can be evaluated, compared to other known events in the past, and estimated. We understand that control room activities were intense and challenging in response to the Covid-19 lockdown, when demand patterns changed dramatically in response to quite new scenarios.[49]

These circumstance aside, we see remarkable continuities in gas distribution control operations over the last half century or more. In 1951, Charnley described the importance of gas forecasting for optimising compression and gas costs, highlighting the significance of weather forecasting and the regular consultations between the gas boards and the Met office. He also outlined the duties of a shift control engineer who: 35

> determines demand for next 24 hours, correcting for rapid variations in temperature; arranging production of peak load gas by various works; directing flow of gas to balance stocks and make us of all available storage; planning daily gas pumping programme for most economical distribution and minimising transmission power charges; accommodating day to day repairs and breakdown when necessary.[50]

In the gas distribution control room that we observed, only gas production was no longer something the shift engineers worried about, but all other tasks were similar, if updated. 36

In contrast, electricity control room engineers do not engage in forecasting, which is managed at transmission level, but manage a more complex set of infrastructure assets than on the gas network. This requires complex calculation and knowledge of system flows, including positive and reactive currents. They may deal with voltage variations coming from solar PV inputs, and need to be alert to which transformers can take directional currents and which cannot. 37

While routine operations may appear mundane, all control engineers are also trained to respond to major incidents, whether caused in their network or requiring a response. At these points, they may potentially be required to work in another region, when they become aware that each control room 'speaks a different language'. Each instruction has to be 'translated' to ensure that they fully understand one another. At the local level, each control 38

48 Tasks such as balancing demand and supply are managed at the transmission (national) level in the UK and not in these distribution control rooms.

49 Precisely because of these conditions, we have been unable to observe these changes and can only report secondary reports and informal communications. At a general level, National Grid have published reports on their response to the changing demand patterns. See NG Summer Outlook (April 2020) **https://www.nationalgrideso.com/document/167541/download** and the National Grid Energy Systems Operator data portal https://data.nationalgrideso.com

50 F. S. Charnley, *Some Aspects of Distribution Control as Applied to Interlinked Undertakings*" (cf. note 20, 704.)

room has its own history, developing a unique institutional culture and way of doing things that is peculiar to that one organisation, and tied to the particularities of the infrastructure in that region. That is, engineers may develop particular skills in relation to the grid's adaptation to heavy industry in one area, or remote rural networks in another. Although the regions are large, covering urban and rural areas, the particular layout of the grid including the legacy of generations of infrastructure, requires attention to different issues, fragilities and weaknesses in the grid. And, as in any small geographically located community, local dialects develop, and routines adapt to the personalities of the engineers, as well as particular shift patterns being adopted over time.

39 What was stressed to us throughout our observations and interviews was primarily the continuity in control room operation, the strict adherence to protocols and routines, alongside the lack of coherence in the grids due to the wide variety of equipment – in age, style, manufacturer and reliability – that they have to manage. Engineers also stressed the combination of planned and responsive activities, and the need to adapt to circumstances, particularly in managing diverse maintenance and repair operations on different sections of the grid at the same time. Shift engineers need to be able to multi-task while maintaining focus on safety and regulations. These things remain constant, while the details are constantly changing. We interpret this to mean that control room engineers are always using their own flexibility and creativity to ensure that the system remains under control. How they achieve this is something that changes over time in both gradual and iterative ways, and in their reflections, some of the more established engineers were able to identify changes that are otherwise not apparent on a day to day basis.

How have control rooms changed in the last three decades?

40 In our discussions with control room staff, and particularly with more experienced control room managers, the primary reflections on change over time followed a retrospective horizon across the span of their careers. The kinds of change that they wanted to discuss with us included the skills for the job, changing recruitment, and to some degree, changing management practices (particularly in relation to different owners, as the businesses were bought and sold between different international conglomerates).

They emphasised first the flexibility of control room engineers to adapt to changing control technologies over the course of their careers. Among the most significant changes concerned the shift to digital systems. Until the 2000s, control room engineers were typically recruited from among field engineers. People who had previously worked on the 'assets' on site, making repairs, fixing faults, installing equipment, were considered to have a knowledge of the system that would equip them to be control room operators. Knowing the equipment and understanding the network were highly valued skills, and engineers with this background could easily translate the systematic diagrams, site locations and fault types into recognisable situations, meaning that they could both envisage how the problem looked on the ground, and communicate effectively with site engineers telephoning in with information from the 'real world'. What's more, as older, more experienced engineers, they would have had time to accrue 'life skills', and could be more robust in the face of emergencies, and more reliable as employees in charge of crucial infrastructure. 41

More recently, though, the shift engineers have realised that (typically) men in their 40s (and, we should add, primarily practical engineers) are often not ideally suited to working in the multi-functional, multi-tasking environment of the contemporary IT-driven control room. 'They're used to doing one job at a time', a shift manager explained to us. 'Here there are time pressures, and so forth, and they don't thrive'. In the last five years, he continued, many have been withdrawn or left the control room, and newer recruitment strategies aim to find younger, more agile, more IT-literate operators who are good multi-taskers and quick learners. These recruits can then be trained and given the 42 knowledge and experience required to manage the system. In fact, one engineer hinted that video gaming, with its requirement to focus on multiple factors and respond quickly and accurately to emerging and unexpected tasks, offered a valuable set of skills, although they hastened to add that system control was not a game. As one of the shift managers told us, his background as an apprentice electrician, later qualifying as an electrical engineer and achieving promotion into the control room was not a career path that would be possible today, and at his age (early 50s), he would certainly not be appointed now. Possible career paths of engineers have thus changed in response to changes in technology, bringing life histories in and out of sync with the technologies of grid control.

43 The training of control room engineers also entailed a combination of absolute rigidity and remarkable flexibility. Following a safety hierarchy that prioritises the safety of staff and public, then the assets, then customer supplies, engineers are trained via a strict sequence of modules that require them to learn system layouts, regulatory requirements, emergency responses and so on. These are specified, approved and regularly updated in liaison with the regulatory authority. However, the time taken to complete the training was highly variable. The priority was in ensuring that the trainee became competent, rather than the time taken to achieve competence. This meant that training schemes could be completed according to the trainees' learning capacity. For example, operational elements of system management were taught by layering up safety management constraints through 5 different levels of training. First, trainees develop IT skills over approximately 6-12 months. Then it may take around 12-18 months to learn about the company generally, another 6 months to learn the low-voltage system, moving up gradually to the next level of system-voltage. All the time, the trainee may be taking on small or non-critical tasks, observing and assisting in the control room, and gradually beginning to operate the control desk under supervision. They pass through to the next stage of training when they have built the confidence to proceed, and when their supervisor agrees that they are competent (as well as passing various kinds of test). Training, in other words, follows a strict pattern in terms of content and progression to the next level of authorisation, following a 'competency profile', but it is also flexible in terms of the time trainees are given to progress to the next stage.

The pace of technological change is such that engineers also have to complete retraining at regular intervals, and in the electricity network, shift managers were also expected to move into the planning section for a year every few years, bringing their operational expertise into the planning of operations, and, at the same time, escaping the gruelling routine of working to shift patterns. Within the control room, shift patterns themselves also combined rigidity and flexibility. While strict rules about rest-periods applied, engineers could work within them to swap shifts to make space for family events, for example, or holidays. And engineers were also expected to display a degree of flexibility in allocating hours when they could be called upon to respond to emergencies. Employee flexibility has also been apparent through the Covid-19 lockdown, with companies reporting that control room engineers have moved into temporary accommodation on-site, so as to avoid the lockdown conditions that might otherwise prevent them from carrying out their duties. 44

The everyday flexibility of engineers could also be seen in relation to the historical rigidities and weaknesses of the networks. Network management, and in particular maintenance regimes, can be evaluated in terms of risk. The ideal is to achieve 100% operation – operation of all of the grid at all times - but design standards always entail degrees of risk around potential losses, outages for maintenance, degrees of redundancy that are affordable in the system, and so forth. Control room engineers work with the unpredictability of asset-failures and faults, using their ingenuity and problem-solving skills within the limits of safety and security rules that are largely treated as absolute. 45

46 In fact, control room systems and control room engineers have adapted to significant system changes in the past two to three decades. The introduction of distributed generation – i.e. the shift from large fossil-fuelled power plants to lower-powered renewable generation sources - means that new knowledge and procedures are required to keep operations safe when flow-directions cannot be calculated. In particular, where legacy assets, such as ageing transformers without remote control, cannot send adequate information through the SCADA system, operators have to be particularly alert to ensure that areas under maintenance are entirely safe.

47 The information system is not based on dynamic modelling, and does not offer prediction, so power flows can be difficult to identify in the current context of increasingly distributed generation (i.e. power now flows in both directions along some parts of the grid). Some parts of the system have excess capacity while others are considerably constrained, and this must be managed by engineers who internalise the flexibility required to adapt to diverse conditions on the network, as well as changing contextual circumstances (from changing weather to local, regional or even national emergencies). Control room engineering can therefore be characterised as a curious combination of routine and exception, banality and intense creativity, tedium and action.

48 The engineers also spent a great deal of time describing their shift patterns, and the changes in shift-patterns they had dealt with throughout their careers. Shift patterns are complex, going through changing cycles of day/evening/night shifts and rest periods, including on-call periods, over the space of around six weeks that ensure that at least one shift manager is on site during the daytime hours when maintenance is mostly scheduled. Throughout the shift, though, there are no scheduled rest breaks. Engineers can operate one another's desks, and co-operate amongst themselves if they need to take a break for refreshment or relief. Some brought their own food (particularly for the night shift) or ordered in sandwiches, while they tended to make rounds of tea and coffee for one another throughout the shift. To this degree, they flexibly managed their own shifts, since taking fixed breaks would require cover, which they accepted as an inefficiency.

As these examples indicate, control room engineers have to manage a very broad range of infrastructure assets of different ages, quality and predictability, based on partial information and through rolling patterns of shift-work. In responding to these challenges they describe multiple forms of flexibility. The demands they face, and the forms of flexibility that are consequently called for gradually shift over time, but at any one moment, day to day practices appear relatively stable. These are not unusual experiences. Other studies of control rooms indicate that people such as shift engineers operate according to their own theories of skill, achievement and 'working well'[51,52,53] and that different forms of flexibility are required as technologies change over time, as complex systems unfold and as 'legacy' and experience mesh with innovation and novelty. Hence we consider adaptability as another form that flexibility can take among control engineers. 49

CONCLUSIONS

In this article we have described how the notion of centralised control emerged as a standard form in network management, and we give a detailed description of everyday distribution control room operation today. In doing so, we show how the operation of system control requires a degree of flexibility among the engineers who operate the control function. Rather than focus on the flexibilities of supply and demand, we have considered the personal qualities of flexibility, both in regard to the daily operations of managing the diverse tasks required in control operations and across 50

51 Lucy Suchman, "Centers of coordination" (cf. note 7)
52 Christian Heath, Paul Luff, *Technology in Action*" (cf. note 13)
53 Antti Silvast, "Monitor Screens of Market Risks: Managing Electricity in a Finnish Control Room", *STS Encounters*, vol. 4, n° 56, 2011, 145-174.

the life course or career-path of control engineers. We have noted the changing demands on control room engineers, and the limits to their flexibility that lead to the retirement of some engineers and the recruitment of those with different sets of skills.

51 From this, our main conclusion is that flexibility can be identified in many areas of the energy system, not merely in the matching of supply and demand. As we learned, flexibility is required to maintain functioning networks, whether that depends on the response rates of equipment or the ability of engineers to extemporise, apply their knowledge and skills to new situations, make judgements and predictions to generate forecasts, or adapt to changing shift-work patterns in their daily lives. Control rooms have emerged in gas and electricity distribution systems along with the development of networks and grids. In both cases, there is a common mentality and approach based on an underlying principle of system-control, alongside a pragmatic acceptance that the system is in fact far from perfectly controllable. The outcome of this ambivalence is that control room engineers must act flexibly in the detail of their work and in how they develop their careers and life-paths. Even in the most rigidly controlled systems, imperfections, errors and breakdowns call for creativity, the application of intelligence to interpret rules and protocols in response to new circumstances. In our view, the multiple histories of diverse kinds of flexibility warrant closer attention.

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