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Energy technology phase-out: Using international analogues to inform 'net zero' heat decarbonisation policy

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June 2021

About ClimateXChange

ClimateXChange (CXC) is Scotland's Centre of Expertise on Climate Change, providing independent advice, research and analysis to support the Scottish Government as it develops and implements policies on adapting to the changing climate and the transition to a low carbon society. CXC is funded by the Scottish Government.

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Acknowledgements

The authors thank members of the project advisory group for their contributions throughout the process of evidence review and peer-review. We also thank the advice and suggestions of members of relevant policy teams at the Scottish Government.

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Executive summary

Introduction

Informal references to history are often made in policy discussions where the envisaged changes are unprecedented and direct evidence of policy effects may be unavailable. Analogous reasoning can also provide familiar narratives and help understanding and engagement among stakeholders and the wider public. The phasing-out of fossil fuel heating and the transition to low carbon heating is in some ways unprecedented. It is characterised by urgency, given the critical importance of the heat sector in achieving Scottish and UK statutory decarbonisation commitments, but also uncertainty, due to the significant challenges associated with possible solutions such as electrification, low carbon heat networks, biofuels and low carbon hydrogen.

Supporting evidence-based responses to the heat decarbonisation challenge requires going beyond informal references to history and undertaking a more systematic evidence review of analogous experiences. This report reviews international evidence of relevant historic experiences from across the energy sector; it also considers more recent relevant experiences in the transport and electricity sectors. The cases reviewed here include natural gas grids, personal transport, electricity supply, electricity metering, transport biofuels and condensing boilers. A number of cross-case insights are also drawn, on topics including the timing of phase-out policies, industrial strategy aspects and overall policy rationales.

Case studies

Gas grid transitions

The transition from ‘town gas’ to natural gas in the 1960s and 1970s is widely cited as a precedent for the envisaged re-purposing of the Great Britain gas grid to run on low carbon hydrogen. A closer look highlights some similarities, but also some important differences. Many millions of end-user appliances would need conversion, relatively minor alterations to the gas distribution grid would be required, but the existing gas transmission system would need a large scale conversion or replacement.

The British conversion to natural gas is not the only relevant experience. At around the same time, ‘city gas’ networks in the Netherlands were also converted. There was less prior gas fuel use in the Netherlands than the UK, and an entirely new transmission system was constructed. To attract customers to the new network, gas prices were benchmarked against rival fuels, with lower unit prices as consumption increased. In both the UK and the Netherlands, gas transitions facilitated a huge increase in energy use for heating, with central heating becoming normal for many.

While these appliance and infrastructure aspects are analogous to the contemporary heating challenge, there are significant differences regarding the fuels involved. Unlike hydrogen, North Sea natural gas was readily abundant, had a much higher thermal capacity and was less toxic than the town gas it replaced, and the improvements in heating service it offered greatly helped public acceptance of the transition. In contrast, hydrogen is seen as preferable to natural gas almost entirely because it releases no carbon emissions upon combustion. There is some potential for better heat control systems to be introduced alongside hydrogen, but this does not offer a qualitative improvement in heating services. Finally, there is a very different institutional context: market liberalisation and privatisation means that a hydrogen transition will require coordination between many dispersed private and public sector actors rather than the central control seen earlier.

Condensing boilers

The introduction of condensing boilers has led to significant carbon emissions reductions from UK buildings over the past two decades. Condensing boilers were first developed and introduced in the Netherlands, by established boiler manufacturers, with support from purchase subsidies and public R&D programmes. By the mid-1990s they represented the majority of boiler sales in the Netherlands, allowing Dutch manufacturers a first-mover advantage in a growing international market. In the UK, low initial take-up rates led to their mandated use at the point of replacement. Condensing boilers present minor levels of disruption for households, but only modest efficiency improvements.

Home energy metering

The phasing-out of analogue energy meters and their replacement by smart meters directly affects millions of end-users. Smart meters have been introduced in differing ways internationally over the last 20 years, with different results. In the UK, the Netherlands and parts of Australia, significant levels of public opposition have been seen, reflecting concerns about data privacy and the perceived lack of a significant and tangible benefit for households. Such opposition led to mandatory implementation plans being relaxed and made voluntary in some cases. As the only European country to rely on energy supply companies rather than regional network operators as the designated implementing body the UK has also faced industry concerns about the impartiality of the roll out process. Overall, the smart meter experience highlights the importance of public engagement in energy policymaking.

Personal transport transitions

Meeting UK and Scottish climate policy targets requires that both heating and transport sectors move from being almost entirely based on fossil fuels to relying almost entirely on zero carbon technologies within a generation – changes that will directly impact the lifestyle of most people. Unlike domestic heating, however, personal transport transition policies in many countries show a clear preference for one technology solution: electrification. This policy consensus is reflected in the setting of phase-out dates for the sale of petrol and diesel vehicles alongside incentives to boost electric vehicle demand. A broad public-private alignment on the transport transition has also encouraged positive feedbacks between public policy measures and industry innovation and supply chain investments. The heat transition currently lacks an equivalent consensus, and diverging views over heating futures are likely to be seen for some time.

Electricity supply sector

There has often been a strong economic rationale underpinning technology phase-out in the electricity sector, with retired generating plants being replaced by cheaper or otherwise superior alternatives. More recently, climate change and other environmental concerns have driven policy efforts to accelerate phase-out in the sector, with mixed results. In some countries, plans for the phase-out of nuclear power have been delayed or even abandoned as their wider implications have become apparent. In Germany, nuclear power phase-out resulted in greater use of coal power, increasing the carbon intensity of electricity and undermining emission reduction efforts. In Japan, the rapid cessation of all nuclear power in the wake of the Fukushima accident raised the price of electricity and contributed to a spike in excess winter deaths. These experiences highlight the risk of urgent responses in phase-out policymaking, and the need to consider knock-on effects.

Transport biofuels

Like hydrogen, biofuels are a low carbon option across heating, transport and power, but concerns over embedded emissions, land use changes and biodiversity impacts have restricted their use. The blending of biofuels with conventional fuels is also restricted due to backwards compatibility issues. As a result, many countries envisage biofuels use being focussed on a few particularly challenging areas e.g. heavy goods transport and aviation. The use of hydrogen for heating has some similarities here, in terms of its recognised potential to enable the decarbonisation of more challenging parts of the economy. Like biofuels, hydrogen production also raises embedded carbon emissions concerns, although given markedly different production processes, restrictions on the sustainable sourcing of biofuels will not be faced by hydrogen in the same way.

Cross-case insights

Phase-out timing

Major infrastructure transitions, such as gas grid repurposing, necessarily rely on an area-based approach rather than individual decision-making. Transitions in off-grid heating, by contrast, may involve individual household decision-making at the point of replacement. Relying on consumer choice, however, will result in varied and uncertain rates of change. To meet statutory net zero targets, a hard date for technology phase-out may prove necessary, possibly ahead of economic lifetime or natural replacement cycles. However, the smart meter experience shows that a mandatory approach with a fixed deadline – for even a relatively minor technological change – can be retracted in the face of public opposition, suggesting that forced asset scrapping could meet significant public resistance in some contexts. This may be avoided by phasing-out over long timescales to avoid creating stranded assets, alongside market creation and innovation support measures. This suggests that net zero heat regulations should involve lengthy notice-periods and occasional step changes rather than multiple gradual changes.

Supply side policy and industrial strategy

As is being seen in the transport sector, some phase-outs are driven by proactive supply side policies and international market competition. Close collaboration between government and businesses were also been seen in Dutch and British gas grid transitions and, at a smaller scale, in R&D policies that led to the development of a commercially available condensing boiler technology in the Netherlands. Industrial strategy that positively engages with incumbent businesses is more challenging when there is no sector-wide consensus on the best way forward, as is currently the case in UK heat decarbonisation. In such circumstances, industrial strategy is more likely to support the technological preferences and capacities of incumbent supply side actors than venture into areas where there is little or no domestic experience.

Hybrid technologies

Hybrid technologies, such as hybrid gas and electric heat pumps, are appealing ways of ameliorating the effects of phase-out because they offer less disruptive and perhaps more affordable solutions, but they may involve some residual emissions, so face concerns about their compatibility with a fully net zero carbon system. They are also likely to require the continued availability of multiple infrastructures, such as gas and electricity networks.

Policy rationales

A number of cases reviewed here highlight the importance of how policy decisions are justified and communicated, suggesting careful attention on how heat decarbonisation policy is developed and presented. Historic gas grid transitions had convincing economic and social rationales, whereas heat decarbonisation is driven mainly by a transnational environmental rationale (but with other benefits in some situations). Many phase-outs have involved replacements that were preferable in multiple ways, and transport sector transition is being enhanced by local air quality benefits, virtuous cycles between public and private strategies and market competition between incumbent and emergent firms. By contrast, public resistance has been seen in cases where collective and individual benefits are less tangible, such as smart metering. Heat technology phase-out as part of net zero policy will be less likely to suffer stakeholder, public and political opposition, and policy reversals, if the overall rationale for action is transparently evidence based, clearly communicated and widely understood.

Glossary

- BECCS: Bioenergy with carbon capture and storage
- BEV: Battery Electric Vehicle, a solely electrically powered vehicle
- CBA: Cost Benefit Analysis
- CCC: UK Committee on Climate Change
- CCS: Carbon Capture and Storage
- DNO: Distribution Network Operator
- DSO: Distribution System Operator
- FAME: Fatty Acid Methyl Ester, a type of biodiesel
- FCEV: Fuel Cell Electric Vehicle
- FFV: Fuel-Flex Vehicle, a vehicle that can run on variable blends of fossil fuel and biofuel.
- HVO: Hydrogenated / Hydrotreated Vegetable Oil, a type of biodiesel.
- ICV: Internal Combustion (Engine) Vehicle.
- IEA: International Energy Agency.
- LEV: Low Emission Vehicle. Generic term used to capture the varying definitions of vehicles permitted under forthcoming national fossil fuel vehicle phase-outs.
- NEV: New Energy Vehicle, the category of vehicles permitted in China under government fossil fuel vehicle phase-out policy.
- PHEV: Plug-in Hybrid Electric Vehicle, vehicle that can be powered by both a battery and an internal combustion engine.
- $PM_{2.5}$: fine particulate matter (≤2.5μm (micrometres) diameter), associated with various respiratory illnesses.
- PM_{10}: particulate matter (≤10μm (micrometres) diameter, associated with various respiratory illnesses.
- PPCA: Powering Past Coal Alliance: an international coalition of governments and organisations that have pledged to phase-out coal power.
- RHI: Renewable Heat Incentive: financial incentive measure which supports renewable heat in the UK.
- ULEV: Ultra-Low Emission Vehicle: the category of vehicles permitted in the UK (and Scotland) under government fossil fuel vehicle phase-out policy.
- VAT: Value Added Tax, a sales / excise tax.

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1 Introduction: the phase-out of fossil fuel heating

Scottish and UK Governments have recently committed to reduce their GHG emissions to ‘net zero’ by 2045 and 2050 respectively (CCC, 2019; Scottish Government, 2019a; HM Government, 2019). Changing the heating systems in buildings from fossil fuel to low carbon is seen as the most “difficult policy and technology challenge to meet our carbon targets” (HM Government, 2017), and as a “far greater challenge” than decarbonising electricity (Howard and Bengherbi, 2016). In order to achieve the net zero target, a low carbon heating system will be required in virtually every property in Scotland by 2045 (CCC, 2019a).

The UK Climate Change Committee (CCC) has recommended that all new domestic buildings’ heating system installations should be low-carbon at least 15 years before these net zero deadlines (CCC, 2019, p200). Substantially increased levels of low carbon heat uptake will be necessary before these dates to ready the supply chain and, at the same time, there is a need for much greater public awareness of the reasons for (and means of) heat decarbonisation (SMF, 2020). Properties off the gas grid – although a small proportion of overall homes – are seen as a ‘low regrets’ part of the overall buildings stock (CCC, 2016) and are a priority for decarbonisation in Scotland and the UK in the 2020s (HM Government, 2017; Scottish Government, 2019b).

Across Europe, a range of different policy instruments seek to increase the diffusion of low carbon heating systems in households and businesses, including information provision, financial incentives and regulations. As national carbon emission reduction targets become more ambitious, the effectiveness of these approaches will be more closely scrutinised. In Scotland and the UK, the approach has so far been essentially market based (Ricardo-AEA, 2015; Gillich et al., 2017) – with limited results. The primary policy instrument – the Renewable Heat incentive (RHI) – has had less impact than expected (PAC, 2018), and there is a considerable gap between the current rate of low carbon heat uptake and that required to meet long-term policy targets (CCC, 2017b; CCC, 2019a).

In this context, a more ‘forceful’ regulatory approach – one that mandates the phase-out of fossil fuel heating systems – may be necessary, alongside informing and incentivising policy instruments. How any such policy mix is designed and implemented will determine its effectiveness and efficiency, in terms of levels of uptake, the use of public and private funds, and the extent to which it equitably distributes the costs and benefits of transition.

This report seeks to inform the design of policy for the phase-out of fossil fuel heating by reviewing relevant historical and ongoing experiences of technology phase-out policy (and, by extension, Phase-in) in the energy sector. Technology phase-out may be driven by government policy or result from emergent technological, economic or social forces; this study is concerned with examples of phase-out that are policy driven, involving either a mandatory approach or more ‘persuasive’ instruments. Technological transitions ordinarily entail the simultaneous phase-out of an existing technology or fuel and the Phase-in of an alternative, and the review considers both the ‘destructive’ and ‘creative’ sides of technology change in the energy sector. Given continuing uncertainties associated with the technological suitability, social acceptability and political feasibility of low carbon heating in Scotland and the UK, useful insights can be drawn from past and ongoing analogous experiences across the wider energy sector. Whilst analogues can help identify potential risks and trade-offs, it is important to consider contextual specifics when assessing experiences that are in some way analogous.

The report is structured as follows: **Section 2** reviews the policy studies literature on different types of policy-driven change, considers the role of analogous reasoning in policy-making and the extent to which knowledge of policy effectiveness may be transferable between different contexts; **Section 3** sets out the evidence review methodology used to carry out the research; **Section 4** presents the results of a wide-ranging review of phase-out policy efforts in the energy sector, across buildings, transport and electricity sectors; **Section 5** summarises the findings and considers their implications for the design of phase-out policy for fossil fuel heating.

This report is accompanied by another ClimateXChange report by the same authors (Kerr and Winskel, 2020), which reviews heat decarbonisation policies in selected European countries. Compared to the country-by-country review of current heat policy approaches in the accompanying report, this report draws on evidence from a wider scope across the energy sector, and over longer timescales, to offer additional and otherwise overlooked insights for the contemporary challenge of heat decarbonisation.

2 Background: policy-driven technology change in the energy sector

This section provides a theoretically informed review of energy and decarbonisation policy. It first reviews analyses of different types of policy instruments and policy mixes (2.1); it then considers the different forms of policy-driven technological change (2.2); finally, it considers the role of analogous reasoning in policy making, in terms of policy transfer between different political jurisdictions, policy domains and time periods (2.3).

2.1 Policy instruments and mixes

There is a growing body of literature that considers the design and mix of policy instruments used to facilitate sustainable energy transitions (Kivimaa and Kern, 2016; Rosenow *et al.*, 2016; Rosenow et al. 2017). A distinction is often made between *market-based instruments* such as grants, loans or a favourable tax regime, and *regulatory instruments* such as emissions standards, fuel standards technology performance standards (Kemp and Pontoglio, 2011a; Li and Ramanathan, 2018).

Market-based policy instruments are sometimes considered a part of ‘new environmental policy instruments’ (NEPI) that have proliferated in recent environmental policy in Europe, replacing a more forceful ‘command and control’ regulatory approach (Jordan et al., 2005; Bomberg, 2007).This trend is associated with distributed governance, where the boundaries between public and private sectors are blurred, with the central state losing some of its authority to transnational organisations, devolved regions or arms-length agencies.

Beyond this, various other typologies are used. Considering the design of an effective policy mix to promote energy efficiency, Rosenow et al. (2016, 2017) use a classification of policy instruments adopted by EU member states which includes: information and feedback, taxation, purchase subsidies, access to capital (loans or financing) and minimum standards (including both voluntary agreements and mandatory regulations) (Rosenow et al., 2016).

In practice there is a huge and complex array of explicit and implicit policies in the UK energy sector (Helm, 2017), with incentivising instruments acting alongside regulations (Rosenow et al., 2017). Large energy users, for example, face both taxes on the emission of certain pollutants, as well as limits on how much they can emit. This mix means that identifying the effectiveness of any single instrument is problematic.

A distinction is also sometimes made between *creative policies* that support the development and deployment of low carbon technologies, and *destructive policies* that destabilise and phase-out carbon intensive industries and activities (Kivimaa and Kern, 2016; Kern et al. 2017). Creative policies include R&D funding, purchase subsidies and public procurement, while destabilising policies include emission limits, reducing subsidy support or tax breaks, or setting a timeframe for the prohibition for established technologies. Other terms used to describe such policy include discontinuation or sun-setting (Rogge and Johnstone, 2017; Hess and Renner, 2019). In practice, sustainable energy transitions will involve a mix of creative and destabilising policies, simultaneously supporting new technologies while phasing-out others. Ultimately, policies that act to support low carbon technologies will simultaneously undermine high carbon alternatives, and vice versa.

It is sometimes suggested that energy policy mixes are imbalanced, in that they involve relatively few destructive policies that inhibit high carbon activity, and emphasise creative policies supporting low carbon innovation (Kivimaa and Kern, 2016; Rogge and Johnstone, 2017). Destabilisation policies such as carbon pricing face the difficult politics of harming existing industries that provide employment and tax revenue (Normann, 2019). Policy support for niche technologies is ordinarily more politically acceptable, but destabilising existing technologies or industries may be necessary to create the conditions for new technologies to proliferate (Turnheim and Geels, 2012; Kivimaa and Kern, 2016; Meckling et al., 2017). Societies are ‘locked-in’ to particular technologies and practices, and rather than merely levelling the playing field, public policy needs to more decisively *tilt* it for ambitious goals to be reached (Normann, 2019).

A related argument is that decarbonisation policy does not sufficiently impact upon incumbent supply chains and producers, and instead tends to direct its focus on consumers or end users (Lazarus et al. 2015; Green and Denniss, 2018). The suggested benefits of a more producer focussed policy include limiting over-supply and spillovers of fossil fuels, and enabling accelerated change by addressing a smaller number of actors (Lazarus, Erickson and Tempest, 2015).

Not all of these claims withstand empirical scrutiny. For example, the UK electricity sector has seen comprehensive supply side decarbonisation policy mixes. The ‘Electricity Market Reform’ mix of a capacity market, carbon price floor, emission performance standard and contracts for difference have stimulated the rapid deployment of renewable energy and a rapidly decarbonising electricity grid (DECC, 2012a; BEIS, 2020a). Change within infrastructure technologies such as electricity networks clearly requires policy that focuses on incumbent supply side actors (Verbong and Geels, 2010; Winskel and Radcliffe, 2014). The extent to which heat is an infrastructure issue depends on how it is provided: in countries such as the UK and the Netherlands where gas networks provide the vast majority of buildings heating, the repurposing of national infrastructure is a possibility – as this report examines in Section 4.1.1, below.

2.2 Policy-driven technology change

Technological innovation is often analysed according to whether it relates to products, processes or organisations (Rennings et al., 2013). A distinction is also commonly made between *incremental* and *radical* innovation (Kemp and Pearson, 2007; Arundel and Kemp, 2009; Rennings et al., 2013). Radical innovation is a break with existing competencies and technologies (Kemp and Pontoglio, 2011b), possibly leading to a wider transition (Kemp and Pearson, 2007). For Garcia and Calantone (2002) radical innovation results in a new market infrastructure and discontinuities at macro and micro levels, for example, the steam engine or the World Wide Web. By contrast, incremental innovation adapts, refines or enhances existing technologies or their production and delivery systems, for example, supersonic passenger aviation. Incremental innovations fit well within the existing systems, while radical innovations often do not.

Policy can support incremental improvements or promote radical change. Setting minimum standards on the emissions intensity of a fossil fuel boiler, for example, may result in an incremental efficiency improvement in boiler design, or if meeting the standard is more challenging, an effective phase-out. Edge and Mckeen-Edwards (2008) distinguish between phase-out policies and outright bans. Phase-out could involve minimum efficiency standards that favour certain technologies, such as condensing boilers or LED lighting. While performance or efficiency standards may not directly ban less advanced technologies, it makes their continued use technically or economically prohibitive.

Whether the transition to low or zero carbon heating requires radical change is partly a definitional issue. Incremental changes such as the introduction of condensing boilers are clearly insufficient to meet net zero policy ambitions. Moving from a fossil fuel boiler to a biofuel or a hydrogen boiler goes beyond incremental innovation as conventionally defined, but is less disruptive than other forms of low carbon heat in some respects, for example, in terms of the end-user experience. Changing from a fossil fuel boiler to a low temperature heat pump system is considered by Beerepoot (2007) as going beyond incremental innovation, but neither radical or systemic. This is not just a technology matter: heat transitions have important social and institutional dimensions, and disruptive innovation may involve new business models, such as ‘heat as a service’ (Marques et al., 2019)

System transition can seek to maintain as much similarity as possible between the existing and the new systems, or there can be a more discontinuous transition with the abandonment and replacement of the existing system (Unruh, 2002). Radical innovation is often thought to predominantly occur in economic *niches*, with the existing socio-technical *regime* (e.g. the dominant practices, technologies and structures of heat provision) associated with incremental change. Winskel and Radcliffe (2014) outline why this model may not be appropriate for contemporary decarbonisation transitions and highlight the role that regime actors can play, especially in transitions that involve ‘infrastructure technologies’ i.e. electricity and gas grids.

Kattirtzi and Winskel (2020) distinguish between different heat decarbonisation pathways for the UK in terms of their disruptive and ‘continuity-based’ characteristics. In this framing, local or community-scale district heating networks are seen as a disruptive supply infrastructure for the UK, both technically and socially. Domestic electric heat pumps are disruptive at the level of individual buildings and electricity distribution grids. The repurposing of the UK gas infrastructure to distribute low carbon gas such as hydrogen is seen as a relatively continuity-based solution, at least for local energy infrastructure and domestic end-users.

2.3 Policy effectiveness, knowledge transfer and analogous reasoning

Policy transfer refers to the process by which policy relevant knowledge – regarding the design of policy instruments, institutional arrangements or ideas relating to the development of policy – is transferred between political jurisdictions (Bomberg and Peterson, 2000; Dolowitz and Marsh, 2000). While early research on policy transfer centred on transfer between governments, the scope has broadened over time to incorporate the role of non-government organisations, the private sector and civil society actors (Lovell, 2016). Globalisation and the ‘information age’ have heightened the apparent rate of transfer, with policy decisions made in a certain jurisdictions increasingly “echoing and influencing those made elsewhere” (Peck, 2011, p.1).

Examples of policy transfer or convergence in recent years include the privatisation of state-owned enterprises since 1980, the adoption of legally independent central banks (Cairney, 2012) and the use of certain renewable energy policies in Europe (Busch and Jörgens, 2012). While policy diffusion may be increasing, diffusion does not necessarily result in simple policy convergence, as highlighted by Radaelli (2005) with respect to the increased use of policy impact assessments in Europe. Policy transfer often involves taking a broad idea or approach to develop a hybrid or modified approach in the recipient context (Rose, 1993; Warren, 2017).

Policy transfer will most commonly take place within a single policy domain; for example, the use of purchase subsidies for renewable heat in one country may inspire their adoption for the same purpose in other jurisdictions. While this review's companion publication (Kerr and Winskel, 2020) focuses on heat policy, this report brings together evidence from across the energy sector, including transport, electricity and buildings sectors. Although policy analogues may be used to inspire rather than imitate, how the wider evidence relates to the heat policy domain requires attention to a set of contextual considerations. Lessons should be drawn with caution because there is inevitable selectivity in the analogues chosen, and they each have particular multifaceted contexts. As Smith (2004) noted, efforts to draw lessons from international experience are often deeply intertwined with domestic politics and local interests.

Disentangling the effect of a single policy initiative or suite of measures in any one location is highly problematic (Sorrell, 2007). For example, in an international review of housing energy efficiency interventions, Ricardo-AEA (2015) concluded that policy effectiveness depended on details of context and design, to the extent that no single intervention could be judged clearly superior to any other. In a similar vein, an International Energy Agency review of policy impact concluded that differences in the effectiveness of specific policies were less significant than differences between countries adopting the same policies – highlighting the importance of the overall policy package, and stakeholder confidence in the overall policy commitment (IEA, 2011). Rather than any universal policy 'winner', therefore, cross-national studies tend toward good practice principles of policy design.

The transferability of evidence across time and space is a key issue in the policy transfer literature (Rose, 1993; Dolowitz and Marsh, 2000; Cairney, 2012). Effective policy transfer between international contexts depends on a degree of similarity in institutions and resources (Rose, 1993). Based on policy evaluations from 30 countries, Warren (2017) considered the transferability of energy demand side management policies. 28 contextual factors were identified, including market structure, energy system structure, energy demand patterns, regulatory structure and cultural familiarity – although only 12 factors were fully assessed by Warren, due a lack of data on factors such as 'cultural familiarity'. The large number of relevant contextual factors and the difficulty in obtaining suitable methods and data to characterise them highlights the challenges of comparing policy knowledge between contexts. Ultimately, Warren (ibid.) used contextual factors to categorise countries into groups with similar contexts, between which policy transfer may be more appropriate.

A primary obstacle to policy transfer is the uncertainty of policy effectiveness in the host country. Determining effectiveness is often contentious, as policy initiatives typically create winners and losers. In energy policy these effects are also difficult to properly determine due to uncertainty over the appropriate counterfactual (Pawson, 2013). For example, UK's Energy Supplier Obligation (ESO) over the decade 2005 to 2015 resulted in the wider uptake of energy efficiency measures (Rosenow et al., 2013). At the same time, however, there was a sharp rise in energy prices, driven by multiple domestic and international factors. Studies analysing the impact of ESO on prices suggest that the overall effect of energy efficiency measures was to lower energy bills (CCC, 2017a; Rosenow et al., 2018). Even so, some politicians associated the ESO with increasing energy costs and it was eventually rolled-back (Mason, 2013).

The multiple factors affecting policy outcomes mean there is perhaps inevitable dispute over complex causes and effects, and the impracticality of running controlled experiments to test policy effectiveness encourages less formal reference to experience that are in some ways analogous. While an analogue cannot ever be a perfect match, partial similarity is often enough to provide useful insight (Giacomini, 2005). Analogous reasoning is a common feature of many policy domains; for example, in international relations foreign policy interventions are often justified or opposed with reference to historical precedents (Khong, 1992; Hehir, 2006; Mumford, 2015). While they can be used to directly inform decisions, analogies can also be used rhetorically to justify decisions to political or wider public audiences (Meierhenrich, 2006; Mumford, 2015). Tierney (2007) differentiates between two functions of analogical reasoning: strategic analogies that mould policy responses and moral analogies that relate to the ethics of potential decisions.

Analogies offer a means to engage with a complex subject in a way that is “familiar or clearly understood” (Meierhenrich, 2006, p. 2). Analogues may not suggest ready-made policy options in the same way as more formal analysis, such as energy system modelling, but instead help to identify potential pitfalls and trade-offs (Watson et al. 2012). Capturing value from analogical reasoning requires a comparison of the context of the precedent and recipient cases, and a limited number of key contextual variables can permit a useful level of comparison. Analogous experience is particularly useful for seemingly unchartered or unprecedented policy problems such as the transition to net zero economies.

3 Methodology: our approach to evidence review

Evidence review methods aim to reduce the selective and opportunistic use of evidence in public policymaking and foster a more systematic and balanced approach. Such methods were originally developed in the medical sciences, and there are challenges to their use in the energy sector. The scale of energy systems make experimental comparison between national contexts difficult, and the social and economic sensitivities mean that energy policy is often highly politicised (Sorrell, 2006). Nevertheless, the use of evidence review methods can signify assessment that is more wide-ranging and transparent than otherwise.

This review involved a mix of selective and systematic methods over three distinct stages: first, a topic selection and scoping phase; second, a review of existing approaches to heat decarbonisation policy in selected countries (see Kerr and Winskel, 2020); third, a systematic review of evidence related to selected energy policy analogues from the energy sector relevant for the design of phase-out policy for fossil fuel heating.

3.1 Stage 1: Topic selection and scoping period

The research topic was developed by the project team and advisors, including the research sponsors, the Scottish Government. A project scoping note outlined the topic focus: the use of a mandatory regulation for energy technology phase-out, and suggested how the review could be carried out. The scoping note was discussed at an advisory group meeting convened by the project team, and this discussion informed the direction and content of the review. In the course of the review, the evidence base developed, the focus was expanded from regulations to wider policy issues (see section 3.3).

3.2 Stage 2: Review of European heat decarbonisation policies

The second stage of the review was to assess existing heat decarbonisation policies in selected European countries. This work was ultimately published as standalone report (see Kerr and Winskel, 2020). Assessing different national policies highlights alternative approaches to the common challenge of heat decarbonisation, and also, provides context for how the wider systematic evidence review presented here can inform phase-out policymaking for fossil fuel heating. This stage also helped identify the search terms for the systematic evidence review.

3.3 Stage 3: Systematic evidence review

3.3.1 Identifying energy sector analogues

Our analogues were identified by a combination of evidence collected for the review of heat decarbonisation policy in selected European countries, reference checking, and through discussion with the project advisory group and Scottish Government representatives; the search terms used for systemic searching are shown in Table 1.

The key terms listed in Table 1 were used in every search alongside Boolean combinations of the secondary terms. Two academic search engines were used: *Science Direct* and *Scopus.* Due to the ubiquity of terms such as 'energy, 'regulation' and 'policy' in the academic and 'grey' policy literature, these key words returned many thousands of results, most of which were of limited relevance. Following systematic review protocols (Speirs et al., 2015), the title, abstract and key words of the first 50 returned articles were read, to provide a selection of relevant articles for review. Checking the references and following the citation trail identified further analogues, with additional ones also identified in discussion with policy advisors and the Scottish Government. The review expanded the focus to include evidence from non-regulatory approaches to phase-out policy, due to the identification of relevant evidence from such approaches[1].

Table 1: Search terms for systematic evidence review

Key terms	Secondary terms
Energy	Phase-out
Policy	Regulation
	Mandatory
	Ban
	Prohibition

The selected cases are some of the most prominently referenced analogues in heat decarbonisation debates. While each case is in some way distinctive, all have relevance for the contemporary policy challenge. Each phase-out analogue involves the concurrent Phase-in of a new technology, with this 'creative' aspect of policymaking often the focus of evidence and analysis, rather than its 'destructive' corollary. Analogues were solely drawn from the energy sector to ensure relevance. Six analogue types were eventually chosen for review:

- **Gas grid transitions:** historic heat transition policies, regularly referred to in contemporary policy discussions.
- **Low efficiency, non-condensing boilers:** these more recent heat policies are also regularly referred to in heat decarbonisation policy discussions.
- **Smart meters and the phase-out of analogue energy meters**: relevant in term of its application to every home and its contemporary setting; it also offers insight on varied policy options internationally.
- **Personal transport vehicles (internal combustion engine) phase-out**: analogous in terms of its reach across the vast majority of the population, the compressed timescale for change, a range of available technology options (electric, liquid fuels, etc.) and the need to upgrade existing infrastructure.

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[1] The review initially set out to focus on regulatory approaches to technology phase-out that mandated change, prohibiting the use or sale of a technology according to a certain timeframe. During the process of identifying analogues it was decided that this focus was too narrow, as it excluded several relevant cases which did not involve the prohibition of use or sale.

- **Transport biofuels**: analogous in terms of the potential use of alternative gas or liquid fuels i.e. biofuels and hydrogen.
- **Electricity supply technology phase-out**: analogous in terms of phase-out timescales and a range of scale and infrastructure issues.

3.3.2 Evidence gathering

Evidence gathering for each analogue was first carried out using academic search engines. Additional searches and specific search terms related each analogue were also undertaken. For example, evidence from countries with prominent ICV phase-out policies was assessed with a targeted search for ‘vehicle’, ‘car’, ‘transport’ ‘phase-out’, ‘ban’, policy’, ‘country X’. Further searching for academic and non-academic evidence was carried out as each case was developed; for example, if biodiesel blending was identified as a significant policy in a particular country, some detail was sought around this aspect.

Only the titles and abstracts of the first 50 returned articles were considered. The use of peer-reviewed, academic literature provides a quality assurance with respect to the evidence considered (Wade and Eyre, 2015). It is also useful as a pragmatic means of restricting evidence from non-academic search engines capable of returning an excessive volume of material. However, the evidence reviewed here was not ultimately restricted to academic sources, with reference checking helping to reveal additional evidence from grey or non-academic sources.

4 Review of phase-out policies in the energy sector

4.1 Buildings sector

This section reviews international research evidence on phase-out policies that have impacted energy use in the existing building stock; three case studies are considered: gas transmission and distribution grids, domestic gas boilers and smart meters.

4.1.1 Gas grid transitions

Before the 1960s the gas used for heating in the **UK** was synthetically produced using coal or oil gasification (with some imported liquefied natural gas for the enrichment of the synthetic gas). This gas was predominantly used for water heating and cooking but became more prevalent for space heating during the 1960s (Dodds and McDowall, 2013; Hanmer and Abram, 2017). It was locally manufactured and piped to homes and business via municipally owned distribution systems (Arapostathis et al., 2013). This ‘town gas’ was roughly 50% hydrogen, 25% methane and 25% carbon monoxide and impurities (Sansom et al., 2019).

In the 1960s, with the discovery of significant quantities of natural gas (predominantly methane) in the UK Continental Shelf, the then system coordinator, the Gas Council, considered converting North Sea natural gas to make it compatible with existing appliances, but ultimately decided that converting appliances to be able to use the new natural gas was preferable, given its superior thermal capacity and lower toxicity (Arapostathis et al., 2013). The chemical difference between manufactured and natural gas meant that this would require the conversion of around 40 million existing end-use devices including boilers and cookers across around 14 million users (Arapostathis et al., 2013; Arapostathis et al., 2014).

Major discoveries of North Sea natural gas were made in 1965, and the decision to convert appliances was made in 1966. The conversion programme ran from 1967-77 and was centrally coordinated by the Gas Council, with the Area Boards (12 regional distribution bodies for town gas) given responsibility for the practical aspects (Arapostathis et al., 2014; Arapostathis et al., 2019). These public bodies had taken over from 1062 gas companies after the nationalisation of the industry in 1948 (Dodds and McDowall, 2013). The actual conversions were, however, frequently conducted by private contracting companies (following training programmes), as the Area Boards lacked the necessary expertise in-house. It has been described as a “centrally coordinated and state-led transition” (Arapostathis et al., 2013). The overall cost was, however, more than double that which was initially predicted (Arapostathis et al., 2019).

The transition required the use of a national grid to transport the natural gas from a small number of gas terminals, replacing the local production of town gas. The existing gas distribution networks required a degree of conversion to make them compatible with the higher pressure national transmission system (Arapostathis et al., 2014). The national transmission system had been introduced in 1964 to deliver re-gasified liquefied natural gas (LNG) to enrich the manufactured town gas. In this way, the introduction of LNG and the national transmission system inadvertently provided a stepping stone to a wider national gas grid (Watson et al., 2012).

The transition involved the conversion of existing boilers, cookers, fires and water heaters rather than their replacement – the conversion process entailed modification of the burner system. Nevertheless, many of the 14million affected properties (around 13million homes, with the rest businesses) had to be visited several times, to plan for, enact and in many cases, address post-conversion issues (CCC, 2018b; Arapostathis et al., 2019). A relatively quick conversion process (by international standards) of around 10 hours was the norm; a longer conversion was deemed to be unacceptable to the public (Arapostathis et al., 2019). Due to the rapid conversions a call-back or post-conversion stage was seen as an integral part of the process; the call-back rate peaked at 25% in 1969 before declining to 12% in 1971 (ibid).

Safety concerns meant that some existing gas appliances couldn't be converted and were made redundant. Customer complaints were, perhaps inevitably, at record levels during this time, with the conversion programme attracting negative media attention (Hanmer and Abram, 2017). Natural gas was, however, promoted in marketing campaigns as a safer alternative to town gas (MacLean et al., 2016) and the conversion programme was presented as having national importance (Arapostathis et al., 2019). For example, the town gas explosion at the Ronan Point housing block in 1968 led the gas authorities to communicate the overall safety benefits of the new gas, helping legitimate the transition (Arapostathis et al., 2013; Arapostathis et al., 2014).

The conversion programme led to a higher level of safety in relation to gas heating and cooking. There were 1193 gas poisoning deaths in 1963, by 1969 the number fell to 250, nearly five times lower (Arapostathis et al., 2014). Maclean et al. suggest that ultimately the transition was necessarily "underpinned by trust … between consumers and gas providers" (MacLean et al., 2016, p.17). While Arapostathis et al. (2019) state that there was a "broad consensus that the conversion process succeeded overall" (p.132). The vertically integrated nature of the industry, and the agency and power of the Gas Council were seen as critical factors in this (p.136).

The natural gas transition coincided with a move toward central heating, away from the then common domestic practice of only heating some rooms (Hanmer and Abram, 2017). The proliferation of central heating systems was partly driven by developments in pump and pipework technology (smaller bore pressurised piping) (ibid., p.6). While more affluent households began to use gas and then electricity for heating and cooking from the 1920s and '30s, poorer households still used coal (Fouquet, 2014). During the 1960s there was no association of central heating with a specific fuel, with coal, oil, gas and electricity all being used. The Clean Air Act of 1956 led to designated smokeless areas where coal was not permitted, and from 1962, grants for converting to gas or electric heaters were available (Hanmer and Abram, 2017).

While the use of central heating was growing before the introduction of natural gas, it was promoted alongside the conversion. The lower cost of natural gas meant that central heating could proliferate (Hanmer and Abram, 2017); only around 30% of British homes had any form of central heating in 1970; by 2018, 85% had natural gas central heating (BEIS, 2019). The move from town gas to natural gas coincided with a three-fold increase in energy supplied for home heating: at its peak in 1969 town gas provided less than 140TWh of energy, while by the completion of the conversion programme in 1977, natural gas was providing nearly 450TWh (Arapostathis et al., 2013). Central heating also improved domestic living conditions by removing the need to transport coal and clean fire places. In sum, natural gas conversion in the UK offered multiple technical, economic and social benefits

The Netherlands also saw a transition to natural gas via a national grid. This was predominantly a shift away from open coal fires with 'city gas' grids distributing manufactured gas to around 2million users for cooking and hot water (but not for space heating) (Correljé and Verbong, 2004; Arapostathis et al., 2019). Although natural gas had been exploited in the Netherlands as early as the late 1940s and 50s, the discovery of a huge reserve in the Groningen Field in 1959 prompted a reassessment of the utility of natural gas (ibid).

Initially, there was some debate between the Dutch Government and the two multinational companies that extracted oil and gas from Groningen – Shell and Exxon – as to how best to profitably exploit domestic natural gas reserves, particularly whether 'small users' (homes and small businesses) rather than larger industrial users would invest in the necessary new equipment and heating systems (Correljé et al., 2003, p.30). It was decided that the potential benefits to (and profits from) involving small users were so significant that a country-wide high-pressure transmission system linking the existing 'city gas' and newly established local distribution systems to the Groningen field was merited.

As a result, a public–private partnership ('Gasunie') between the Dutch state (50%), Shell (25%) and ExxonMobil (25%) was founded to transmit and sell the gas – a novel partnership for a capitalist country of that era (Correljé and Verbong, 2004). Competitive pricing was used to persuade enough households to join the grid to make the transition profitable. The pricing strategy linked the price of gas to existing fuels, and offered lower unit costs with higher levels of consumption (Correljé and Verbong, 2004).

Many existing city-wide distribution grids had to be converted to be able to take the higher calorific natural gas (some of the city grids closer to Groningen had already been converted); elsewhere, new distribution grids were constructed (Correljé and Verbong, 2004). Just as in the UK, existing domestic appliances had to be converted or replaced if they were too old, with existing city gas staff re-trained for this work. (Correljé et al., 2003. p.60).

The Dutch Government set out the main principles of the transition in a White Paper in 1962 and construction of the high pressure transmission network beginning in 1963 (Correljé et al., 2003). By 1969, 80% of Dutch houses were connected to the national grid. Correljé et al. (2003) note the importance of collaboration between the Government, the private sector and incumbent energy stakeholders, especially Dutch State Mines (DSM), who had a share of the new venture as a form of compensation. This collaborative approach was prevalent in Dutch governance at the time:

> *"The various interests associated with the pre-existing energy supply system were either given favourable positions within the new structure, as with DSM, and the municipal town gas companies that were endowed with the task to distribute natural gas, or compensated and bought out, like the steel mill Hoogovens."* (Correljé et al., 2003, p.37).

The move from coal to gas saw the Dutch Government suggest in 1969 that all remaining coal mines should be closed by 1975 – a far-reaching public intervention, and despite pressure on the coal industry after the discovery of the Groningen gas field, ultimately a political decision, not a business one (Normann, 2019, p.7). Kemp (2010) describes the overall transition from coal to natural gas as "government induced" (p.294), with the Dutch State having a clear long term view, and the speed of transition was considered exceptional.

Although the Dutch gas transition happened very quickly, in less than a decade, it is important to highlight some supportive preconditions: existing infrastructure, including some city-wide grids that had developed in the 1950s, and a widespread public familiarity with gas in domestic settings (Correljé and Verbong, 2004). There were also favourable international factors: for example, cheaper international sources of coal and the anticipated rise of affordable nuclear power meant that there was a belief that for the newly discovered gas to be economic that it had to be exploited quickly (Rotmans et al., 2001).

The **Isle of Man** converted to natural gas much later than the British mainland, and in an age of mainly privately-owned energy businesses in the UK. This transition involved moving from an LPG/air mixture to natural gas. In 2003, 15,000 customers in the capital, Douglas were converted, but it took until 2011 for the rest of the island's homes (7,000 - 8,000) to be converted in a 2-year programme. The properties on LPG had higher bills and a restricted choice of appliances, while the grid operator Manx Gas had to ensure the costly maintenance of the old LPG system (MacLean et al., 2016; Frazer-Nash Consultancy, 2018). Although small in scale, there was an emphasis on public and stakeholder engagement throughout (MacLean et al., 2016).

4.1.2 Domestic boiler transitions

A condensing fossil fuel boiler improves on the efficiency of a non-condensing boiler by extracting the latent heat from exhaust gases. Thermal efficiency is normally over 90% in condensing boilers, 10-12% higher than the most efficient non-condensing boiler (Weber et al., 2002; Palmer and Cooper, 2013). While condensing boiler technology has been available since the 1930s, it was not until the 1970s and '80s that it began to reach the domestic mass market (Banks, 2005). It was prevalent in **the Netherlands** many years before it became popular in the UK. By 1995, 50% of boilers sold in the Netherlands were condensing, compared to less than 3% in the UK (Weber et al., 2002).

In the 1970s, Gasunie (the part state-owned company that owns and runs the Dutch gas transmission system) and the Dutch national energy agency (NEOM), supported the development of a prototype condensing boiler for the Dutch market as a means of reducing national energy consumption (ibid). Boiler manufacturers were asked to develop the technology further, with six manufacturers eventually developing different viable models. As there was a shortage of installers able to deal with the new technology, NEOM also began a training programme. Technology development and deployment was supported by subsidies (funded by national government and the gas distribution companies) from the early 1980s onwards (ECI, 1999b; Weber et al., 2002). Initially considered too expensive and difficult to control, the subsidy programme was an important means of signalling that the technology was reliable and endorsed by government (Weber et al., 2002). Subsidies were available at varying rates over a number of years. Weber et al. (2002) state that in 1995 the subsidy programme in the Netherlands reduced payback on a condensing boiler from about 7 years to about 4 and a half.

The relatively early popularity of condensing boilers in the Netherlands meant that a mandatory regulatory approach for boiler replacements in existing buildings wasn't deemed necessary (Filippidou et al., 2016; Honoré, 2018); for new buildings, regulations ensured only condensing boilers were permitted from 1998 (Beerepoot, 2007). The early development and diffusion also gave Dutch boiler manufacturers a competitive advantage to sell into the wider international markets for condensing technology that eventually developed. The EU Eco-Design Directive effectively made condensing boilers mandatory across the EU from 2015 (VHK, 2019).

In the **UK**, the use of condensing boilers for boiler replacements became mandatory for gas boilers in 2005 and for oil boilers in 2007. Mandatory standards were first announced in the 2003 Energy White Paper and were implemented via the 2005 revision of building standards (Mallaburn and Eyre, 2013). The regulations stated that replacement systems must be rated SEDBUK (Seasonal Efficiency of Domestic Boilers in the UK) 'A' or 'B', requiring a minimum efficiency of 86%, and necessitating the use of a condensing boiler[2]. The regulation was seen as effective given the hard end date and easy enforceability via gas safety checks (Elwell et al., 2015). The regulatory mandate was preceded by a 'cashback' subsidy programme for condensing boilers (starting from the mid-1990s, with the subsidy increased in 1999) (Weber et al., 2002; Killip, 2013). There was also (briefly) a cashback subsidy available for the installer of a condensing boiler (Weber et al., 2002).

Condensing boilers comprised just 0.5% of the UK market in 1995; by 2003 (when the mandatory standard was first announced) this had reached 3.3%, and by 2006 when condensing boilers were required, 14.8% (Utley and Shorrock, 2008). The uptake of condensing boilers prior to the 2003 announcement was considered slow (Mallaburn and Eyre, 2013) and the sharp increase in uptake between 2003-2006 suggests a degree of 'policy signalling', with the announcement of a mandatory requirement encouraging greater uptake before the regulation actually took effect. This uptake was partly led by larger market actors such as British Gas beginning to install condensing boilers ahead of the mandatory requirement (Inman, 2005); by 2017, 66% of households had some form of condensing boiler (OFGEM, 2019).

Killip (2013) describes how a 'market transformation' approach successfully promoted condensing boilers, with financial incentives followed by voluntary standards and then mandatory ones; he suggests that voluntary standards should not only precede mandatory standards but also be raised when mandatory standards are introduced, to promote further innovation. Hanmer & Abram (2017) argue that it was relatively straightforward to make condensing boilers mandatory, as they were similar in terms of dimensions and connections to existing boilers and didn't require any other changes to the wider heating system. However, the change did present some challenges, in terms of a lack of awareness and skills in the supply chain (Mallaburn and Eyre, 2013). At the point when the new boilers were made mandatory, there was significant public and industry concern relating to their reliability, maintenance costs and lifetime (Inman, 2005). This uncertainty is partly attributable to the conservatism of heating industry professionals (Banks, 2005; Kerr and Winskel, 2018).

In England, the 2018 'Boiler Plus' amendments to building standards required boiler efficiency to be at least 92%[3]. Alongside this, boiler replacement was also now required to involve the installation of timer and thermostat controls (if not already fitted), and additional energy efficiency improvements for the replacement of a combination boiler e.g. flue gas heat recovery, smart heating controls etc. (BEIS, 2017; HM Government, 2018).

Reviewing the introduction of condensing boilers in the UK, the Netherlands, France and Germany, Weber et al. (2002) concluded that the involvement of a wide-ranging set of actors (manufacturers, installers etc.) was an important way to ensure policy

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[2] Exemptions were possible if this was considered too impractical or costly e.g. range cookers (Elwell et al., 2015).

[3] Scotland, Wales and Northern Ireland are exempt.

effectiveness. While a small group of vested actors was seen as a problem in the promotion of condensing boilers in the UK in the 1990s, in the Netherlands a large number of associated actors enabled the continuity and expansion of the programme.

As well as the Netherlands and the UK, other European countries saw similar transitions to condensing gas boilers. For example, in **Ireland** a minimum seasonal net efficiency of 86% was required for all new and replacement gas and oil boilers installed from March 2008; this could only be met by condensing boilers. The requirement was applied via an update to part ‘L’ of Irish building regulation (conservation of fuel and energy) (DCENR, 2009; Dennehy et al., 2019) and came into effect soon after the UK regulations, with the UK and Irish markets closely linked.

4.1.3 Smart meter transitions

Smart meters (for electricity or gas) are able to record the amount of energy consumed and communicate this to the energy supplier. Smart meters offer benefit, in principle, to energy suppliers, network operators and consumers. Supplier benefits include reduced meter readings and the ability to offer time-of-use tariffs to customers; network operators are able to better understand energy demand patterns and thus improve the efficiency of energy system operation, while consumer benefits mainly arise from the potential to make energy savings (ultimately through behaviour changes) (DECC, 2014; ICCS-NTUA and AF Mercados EMI, 2015; HM Government and Ofgem, 2017). As part of the EU’s Third Energy Package in 2009, member states were required to implement smart meters in properties (homes and some businesses), where it was deemed cost-effective (DECC, 2014).

The EU Energy Efficiency Directive 2012 introduced minimum functional requirements to smart meters in Europe – for example, consumer rights to access at least the previous 24 months of consumption data (DECC, 2013). Even so, meter functionality has varied across Europe in a number of ways – for example, how often readings are taken (European Commission DG Energy, 2019). Following cost benefit assessments (CBAs), many countries have implemented a mandatory approach to their smart meter implementation programme – though with some notable exceptions, including the UK and the Netherlands (Zhou and Brown, 2017; National Audit Office, 2018).

Italy was the first European country to begin a roll-out programme in 2001 with around 98% of properties having a smart electricity meter by 2011; as of 2018 it has the most smart meters installed of any country in Europe (European Commission DG Energy, 2019). A smart gas meter roll-out began in 2008, with a target of 85% penetration by 2023 (ibid).

The electricity meter roll-out in Italy was led by the Distributed Supply Operator (DSO) ENEL which, in the early-2000s, was responsible for 85% of electricity customers. ENEL Distribuzione considered it cost-effective to roll-out smart meters to all their customers, given the reduced need for manual meter readings, management cost savings and reduced energy losses and thefts (Darby, 2009), and this target was achieved by 2006 (Piti et al., 2016). After this, the National Regulatory Authority made smart meters mandatory for all other DSOs (European Commission, 2014a; Piti et al., 2016).

The cost per meter of the roll-out in Italy has been one of the lowest in Europe, partly because it was carried out by a single large DSO (ENEL) with resultant economies of scale (Piti et al., 2016). However, this first generation of smart meters had relatively low functionality, for example, recording only 3 values a month and with the only communication via the electric power line rather than a wireless network (CMA, 2016).

Whilst it is thought that the roll-out of smart meters in Italy helped to stimulate the EU Directive that required a CBA on smart meters in all member states (Piti et al., 2016), the first generation of smart meters were not compliant with the functional requirements eventually imposed by the EC and the roll-out of a second generation of smart meters is currently under-way in Italy (European Commission DG Energy, 2019). The second generation was commissioned roughly at the end of the life of the first, around 15 years from installation. It incorporated a real time energy usage in-home display and 15 minute meter readings (and thus the potential for time-of-use tariffs) (Piti et al., 2016).

In the **UK**, the initial announcement of smart meter roll-out in 2008 referred to a mandatory installation requirement on energy suppliers (Darby, 2009). This was effectively removed in 2012, when the government required energy suppliers to take 'all reasonable steps' to install smart meters (National Audit Office, 2018). At the time, a mandatory approach was thought likely to lead to resistance from consumers and so be counter-productive (DECC, 2012b). Even so, the government forecasted that over 90% of homes would have a smart meter by 2020. There has been a suggested misrepresentation on the part of energy suppliers, and misunderstanding on the part of consumers as to whether there is a mandatory requirement, or not, ever since (Buchanan et al., 2016; National Audit Office, 2018; Sovacool et al., 2019).

In 2013, the rollout period was extended from 2019 to 2020, with all consumers required to have been *offered* a smart meter by the end of 2020 (BEIS, 2018d). In 2019, the roll-out period was again extended, this time to the end of 2024 (Ambrose, 2019). The Covid-19 pandemic has resulted in a further 6 months' extension to June 2025.

The UK differs from other EU countries in its roll-out plan in a number of ways: it requires an in-home display (IHD) and offer of a smart gas meter (where applicable) alongside a smart electricity meter (most EU countries have simply required the electricity meter, although gas meter roll-out is becoming more common), and responsibility for implementation in the UK lies with energy suppliers / retailers rather than network operators (DNOs) (National Audit Office, 2018; Sovacool et al., 2019). The leading role of energy suppliers is thought responsible for the first generation of smart meters in the UK losing their smart functionality (they 'go dumb' whenever users switch supplier and are unable to send meter readings to the new supplier). This first generation are to be replaced within the new roll-out period. The replacements and the much higher than anticipated marketing budgets (required to encourage a reticent public) have escalated the cost of roll-out (National Audit Office, 2018). To help address privacy concerns, the user can decide the frequency with which the supplier can collect data – half hourly, daily or monthly – and whether the supplier is able to share this data with other companies.

The UK is the only country in the EU that adopted a model of energy supplier responsibility for smart meters (UK energy suppliers were made responsible for domestic energy meters in 2003) (National Audit Office, 2018). This was justified on the grounds that supplier competition would be the best way to ensure efficient implementation, that energy suppliers had a closer relationship with customers than energy network operators, and that it would take time to re-regulate responsibility for the meter to the network operator (DECC, 2009; DECC, 2011; PAC, 2012; National Audit Office, 2018).

Sovacool et al. (2019, p.772) highlighted that the model of supplier responsibility is problematic: it makes an area based approach more difficult as households in one area may have many different energy suppliers. As government policy appraisals recognised, a supplier-led model is also more likely to result in problems with meter interoperability e.g. losing their smart functionality (DECC, 2009, p. 19). There are also low levels of trust associated with energy suppliers/retailers in the UK (Sovacool et al., 2019). All other EU countries give distribution network/system operators responsibility for implementation, although in Australia and New Zealand an energy supplier led roll-out has also been adopted (Lovell, 2017).

The Netherlands also initially planned a mandatory programme, but it was made optional after significant public opposition, on grounds of privacy and also the distribution of costs and benefits (there were obvious benefits for the suppliers but it was less clear how consumers would benefit) (Van Aubel and Poll, 2019; Zhou and Brown, 2017). Households and businesses in the Netherlands can refuse a smart meter altogether, or they can install one but opt out of certain functionalities, such as automatically sending readings (Zhou and Brown, 2017).

Another example of a shift from a mandatory to a voluntary programme is **Australia** (Lovell, 2017). Here, the initial mandatory approach in 2008 was seen as informed by global precedents, but was abandoned largely as a result of a perceived negative experience in the State of Victoria, and by contrast, the perceived effectiveness of a voluntary, retailer-led approach in New Zealand (Lovell, 2017). The roll-out in Victoria received very negative media coverage largely due to its association with electricity bill increases – to the extent that it became an election issue (PAC, 2012), while the New Zealand approach was seen as effective due to its widespread implementation without price increases (Lovell, 2016). However, the New Zealand roll-out suffers from a lack of technology standardisation, with a variety of meter types (Stephenson et al., 2018).

Zhou and Brown (2017) reviewed smart meter deployment policies in Europe, including mandatory approaches in Finland, Sweden and Denmark. In **Finland,** a CBA in 2008 determined that smart meter roll-out would be cost-effective, with DSOs made responsible for implementation in 2009. While a target of 80% penetration was set for 2013, ultimately 100% was achieved by this date (European Commission DG Energy, 2019). Roll-out was financed by an increase in electricity prices, set at 2.8% p.a. in 2012. Finnish consumers are seen as generally accepting of the benefits offered by smart meters and not concerned with privacy issues (Zhou and Brown, 2017).

In **Sweden**, smart meter roll-out was the indirect result of the national Government mandating monthly meter readings in 2003, with Swedish DSOs deciding that the introduction of smart meters was a cost-effective means of responding (Leysen, 2018). Although 100% implementation was achieved by 2009 (in-line with the mandate) the meters introduced by the DSOs varied in terms of functionality. As of 2014, only 20% could measure hourly, with the rest only able to take monthly readings (Leysen, 2018). Since 2013, there has been a further legal requirement for any customer wishing to use an hourly based time of use tariff to have hourly smart metering technology (CMA, 2016). The cost of the roll-out in Sweden is ultimately borne by the consumers, as a use of system levy (Zhou and Brown, 2017).

In **Denmark** in 2013, a few months after a positive economic assessment from a CBA of the impact of smart meter roll out, the national government mandated smart meters in all homes by 2020. Minimum performance requirements for readings at least every 15 minutes were required (Zhou and Brown, 2017). By 2017, nearly 80% of Danish homes were covered (EC DG Energy, 2019). Hourly electric meter readings had already been mandated for larger consumers between 2003 and 2005.

In **Germany**, after a CBA in 2013 (Ernst & Young, 2013) it was decided that smart meters would only be cost-effective for homes that consumed a large amount of energy, and were only mandated for new buildings, homes engaging in a major renovation and homes with over 6,000 kWh annual electricity consumption (from 2020) (NAO, 2018). The CBA assumed particularly low levels of consumer saving and peak load shifting (relative to assessments in other European countries) (Zhou and Brown, 2017). Privacy concerns were also prominently vocalised in Germany (Alejandro et al., 2014).

There are also generic issues related to smart meter financing. These include considerations over the cost and revenue structure of the implementation body, with the cost often borne by the DSO or retail/supply company, but ultimately passed to consumers. According to a European Commission review, “the financing of smart metering is mostly secured through an adequate remuneration of the Regulatory Asset Base via network tariffs”[4] (European Commission, 2014a, p.22). In countries where this approach was not initially followed (Denmark, Sweden, Italy and the UK) it later became the case. In Denmark, Sweden and Italy, roll out was initially financed by the DSOs’ own funds, with remuneration via network tariffs only introduced at a later stage (European Commission, 2014a).

4.2 Transport sector

There is a vast regulatory framework that governs the sale and operation of the different types of private and public transport. This section focuses on two aspects: firstly, policies designed to phase-out internal combustion engine vehicles (ICVs), simultaneously phasing-in low emission vehicles (LEVs); and secondly, policies that promote the replacement of fossil transport fuels with biofuels.

4.2.1 Vehicles

Many national and regional governments have announced phase-out dates for the sale of new internal combustion vehicles (ICVs) in recent years. These initiatives sit alongside longer standing financial and non-financial incentives to promote the use of low emission vehicles (LEV)[5].

What constitutes an LEV varies between countries: it will normally include fully ‘battery electric vehicles’ (BEVs), but potentially also certain hybrid vehicles and hydrogen fuel cell vehicles. Different terms are used in different jurisdictions to refer to different subsets of LEVs, for example, ‘New Energy Vehicles’ (NEVs) is used in China and ‘Ultra Low Emission Vehicles’ (ULEVs) is used in the UK (see Table 2 for the details of which vehicles are included). In this section we use LEVs as a broad term covering different technologies.

Meckling and Nahm (2019) highlight that the recent upsurge in national phase-out dates for new ICV sales are a form of ‘policy signalling’, intended to give the existing automotive industry the confidence to develop and manufacture new technologies. The authors suggest that phase-out goals announced between 2016-18 were driven by global market competition, with a race for market share in emerging green industries, “regardless of whether substantive policies to drive vehicle electrification have already taken place” (ibid., p.470). Only a few countries are following a solely environmental rationale. Those with existing or emerging automotive industries often seek industrial renewal or upgrading. Such policy signalling is directed toward consumers as well as

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[4] ‘Network tariffs’ refers to use of system levies or network costs that are charged to energy bills.

[5] Low Emission Vehicles (LEVs): what constitutes a LEV varies by jurisdiction. In this section ‘LEV’ is used to apply to the different definitions that are used in each country.

manufacturers, with the market uptake of LEVs likely to pick-up well before ICV sale bans come into effect (Brand and Anable, 2019).

In **Norway**, fiscal incentives for electric vehicles (EVs) in the form of tax exemptions (reflecting a 'polluter pays' principle that low emission vehicles should be cheaper than high emission vehicles) have existed since the early 1990s. Specific measures include exemptions to vehicle registration tax (since 1996), toll road charges (1997) and VAT (2001). Additionally, other incentives include access to bus lanes and free municipal parking (Langeland et al., 2018). Together, these measures have led to Norway having the largest EV market in the world (proportional to overall vehicle stock) (Figenbaum, 2017). The policies promoting EVs operate within a favourable wider context in Norway. Around 75% of households are able to park on their own land (the equivalent figure in England is 60%[6]) and, given the prevalence of electric heating in Norway, most households have sufficient power capacity to charge their vehicle (Figenbaum, 2017). The first major public investment in EV charging infrastructure (€6 million) was made in 2009 (Hall and Lutsey, 2017), with a policy commitment to install at least one charging station every 50 km by 2017 (Blakeman et al., 2019).

Table 2: New vehicle sale restrictions, selected countries

Country	Target announced	Target date and description	Permitted vehicle types
Norway	2016	**2025** – all new passenger cars and light vans will be zero emission vehicles (ZEVs) **2030** – all new HGVs, 75% long distance coaches and 50% new trucks shall be ZEVs	'Zero emission vehicles': Full electric and hydrogen fuel cell vehicles
China	2017	TBD	'New Energy Vehicles' (NEVs): battery electric, plug-in hybrid and hydrogen fuel cell vehicles
France	2017	**2040**: end of the sale of new petrol and diesel cars	Government announcement did not stipulate which types of cars would be permitted.
Germany	2016	**2030**: new vehicles to be 'emission free'	Types of vehicle permitted has not yet been defined
Netherlands	2017	**2030**: all new cars to be '100% emission free'	Zero emission vehicles: battery electric, hydrogen fuel cell vehicles (unclear whether it includes PHEV)
UK	2017 (revised 2020)	**2030** (previously 2035 and 2040): end the sale of new conventional petrol and diesel cars and vans. Some hybrid vehicles can be sold until 2035.	'Ultra-Low Emission Vehicles': battery electric and hydrogen fuel cell vehicles (previously included plug-in hybrid vehicles)

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[6] See *English Housing Survey*, Table 3.2

		2030: central government car fleet to be ultra-low emission[7]	
Scotland	2017	**2030**: phase-out the need for new petrol and diesel cars and vans **2030**: phase-out the need for petrol and diesel vehicles in public sector fleets	'Ultra-Low Emission Vehicles': not yet defined

(Sources: Fridstrøm and Østli, 2016; Norsk elbilforening, 2018; Meckling and Nahm, 2019)

In 2016, the Norwegian Transport Agency set targets for all new passenger cars and transit buses to be either full electric or hydrogen fuel cell electric vehicles by 2025. In 2030, the same target applies to all light duty freight, with lower proportions set for inter-city buses and heavy-duty vehicles (Fridstrøm and Østli, 2016). Biofuels are to be used to reduce emissions from transport in the 2020s and 2030s, but as new vehicles are increasingly full electric or fuel cell vehicles, there will ultimately only be scope for biofuel use in shipping, aviation and some larger vehicles (Sollie, 2018). The government plans to support these targets via the tax system and other incentives rather than a mandatory approach (Norsk elbilforening, 2018; Deuten et al., 2020). The National Transportation Plan containing the 2025 and 2030 targets was adopted by the Norwegian parliament in 2017, but is not legally binding (Meckling and Nahm, 2019).

In **China**, subsides have existed for producers and consumers of LEVs for over a decade (Yang et al., 2019). The value of the subsidies has been gradually reduced in this time, and the minimum range that a vehicle must achieve to qualify has been increased. Consumer subsidies were planned to be removed entirely in 2020, with a mandated requirement for manufacturers to supply a certain proportion of LEVs seen as the main market driving mechanism from 2020 onwards (ICCT, 2019a; Sioshansi and Webb, 2019). In 2020, the government decided to continue purchase subsidy support until 2022 (as part of a Covid-19 economic stimulus), but again increasing the range that a vehicle must be capable of to receive the subsidy[8].

ICV phase-out in China does not yet have a formal timeline, and is expected to vary by region, with the Hainan Island province leading the way with a ban on the sale of ICVs from 2030, and with all replacement public sector vehicles (buses, government vehicles) to be 'new energy vehicles' (NEVs) from 2020 (China Daily, 2019).

Alongside this regional approach, the Chinese government has also introduced supply side measures that prohibit the construction of new vehicle factories unless they produce a certain level of EVs. Public procurement rules are also used to promote NEVs; since 2014, at least 30% of vehicles procured in the public service have been required to be NEVs in some cities, with some provinces also setting a minimum proportion of new vehicles that must be NEV in taxi and ride-hailing fleets (ICCT, 2019c). The inclusion of plug-in hybrids in the current definition of NEVs leaves the door open for

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[7] Government want to see 'similar ambition from local government and other public sector fleets' (DfT, 2018)

[8] Prior to 2019 the minimum range to receive a subsidy was 150km, since then it has been 250km and will move to 300km in 2020; see: https://www.electrive.com/2020/04/24/china-extends-nev-subsidies-til-2022/#:~:text=Only%20a%20few%20days%20ago,tax%20in%202021%20and%202022.

future biofuel use, although a vehicle is required to be a ‘flex-fuel’ hybrid if it goes above a threshold level of biofuel use (Lade et al., 2018). There are also various non-financial incentives promoting NEVs in different Chinese regions. There are currently c.500,000 EV charging stations in China, with a mix of state owned companies, battery manufacturers and EV manufacturers carrying out the installations (IEA, 2020).

Meckling and Nahm (2019) see ICV phase-out policy in China as part of a government strategy to ensure Chinese firms gain a large stake in an emerging global industry. Chinese firms had failed to compete with international firms in the global ICV car market, but with existing Chinese expertise in battery production and a perceived reluctance of global manufacturers to commit to EVs, an opportunity for industrial upgrading has been identified by the Chinese Government. Another primary driver for the planned phase-out in China is to reduce local air pollution, with reduction in GHG emissions seen as a secondary motivation (Sioshansi and Webb, 2019). Unlike some other national ICV bans, the Chinese ban is seen as being built on a comprehensive set of policies to promote NEV uptake and production (Meckling and Nahm, 2019).

California accounts for around half of LEV sales in the USA, despite accounting for only 12% of the population (ICCT, 2017). Alongside federal incentives for LEV purchases (ranging from $2,500-$7,500, depending on the vehicle’s battery capacity), there are additional state-level incentives for lower income buyers to purchase LEVs and non-financial incentives such as access to high occupancy vehicle lanes (ICCT, 2017). There has also been mandatory public procurement requirements for LEVs in California since 1990 (Bedsworth and Taylor, 2007; ICCT, 2019c). A sales mandate required zero emission vehicles (effectively full electric vehicles) to constitute 2% of the sales of large automobile manufacturers from 1998, 5% from 2001 and 10% from 2003 (Bedsworth and Taylor, 2007). While some argue that the mandate was ineffective, as the cost and performance of zero emission vehicles did not improve at the anticipated rate, there were longer term benefits: for example, in improving the performance of hybrid and conventional vehicles (Burke et al., 2000).

Regulations in California currently require the equivalent of 8% of sales to be full electric vehicles by 2025, via a credit based system in which hybrid vehicles can contribute to the target[9] (ICCT, 2017). This approach is seen as overcoming a barrier to LEV adoption by increasing the choice of LEV models on the market. The mandated LEVs are required to be ‘made available for sale’. The Californian regulations have been adopted by several other states, and now apply to nearly 30% of the US market (ICCT, 2017).

In the **UK,** a 2017 plan for reducing local air pollution (DEFRA and DfT, 2017) and the 2018 ‘Road to Zero’ transport strategy (DfT, 2018) stated that the government would “end the sale of new conventional petrol and diesel cars and vans by 2040” with a view to transport being fully decarbonised by 2050. The UK government asserted that it first announced its intention to end ‘conventional car and van sales’ by 2040 in 2011, providing the beginning of a tentative lead-in period (DEFRA and DfT, 2017).

The 2040 target faced criticism due to ambiguity over the definition of an Ultra-Low Emission Vehicle (ULEV) (those permissible for sale after 2040), and whether this

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[9] Credit is gained for greater use of electricity and a vehicle having a higher range; 8% is the equivalent level if the target was met by full electric vehicles.

definition included plug-in hybrid vehicles; the date, 2040, was also seen as late compared to other countries with similar emission reduction targets, and inconsistent with the UK's 'net zero' by 2050 economy-wide decarbonisation target (UKERC, 2018; House of Commons, 2018; Brand and Anable, 2019). Modelling by the UK Energy Research Centre (UKERC) suggested that the UK's emission reduction targets would not be met unless all ICV (including plug-in hybrids) were prohibited from 2030 (Brand and Anable, 2019).

In early 2020, the UK government brought forward the phase-out date to 2035 and removed hybrid vehicles from the ULEV definition (HM Government, 2020a). Around the time of this announcement the Transport Secretary suggested that a further move was possible, after a period of further consultation, and in November 2020 the phase-out date for the sale of new petrol and diesel cars and vans was brought forwards to 2030, with all vehicles being required to have "significant zero emissions capability" (plug-in and full hybrids still permitted) from 2030, and be 100% zero emissions from 2035 (with hybrids no longer permitted) (HM Government, 2020b).

Although this phase-out timeframe is thought to provide manufacturers with market certainty, parts of the incumbent industry were seen as a major barrier to change (Brand et al., 2020). The changes to policy and in particular the changing of the definition of what vehicles are permissible has resulted in some criticism, particularly from those that have recently bought hybrid vehicles (with resale value likely to be affected) (SMMT, 2020). PHEVs currently comprise the majority of the EV stock in the UK (see Table 3). There are currently 1,282 passenger cars per public EV charging point in the UK. In November 2020 the Government announced £1.3bn of investment in charging infrastructure (HM Government, 2020b).

Table 3: Electric vehicle penetration rates, selected countries

	EV charging stations	**Passenger cars**	**BEVs**	**PHEV**	**Total EVs**	**Total EVs (%)**	**Cars to charge points ratio**	**EVs to charge points ratio**
China	516,000	210,000,000	2,581,000	768,000	3,349,000	2	407	6
France	38,099	33,020,132	192,008	70,807	262,815	1	867	7
Germany	40,412	47,095,784	178,309	162,495	340,804	1	1165	8
Netherlands	55,739	8,373,244	116,148	97,553	213,701	3	150	4
Norway	16,386	2,700,000	239,105	111,756	350,861	13	165	21
UK	27,236	34,887,915	117,653	187,315	304,968	1	1281	11
Japan	30,394	62,025,916	152,000	142,000	294,000	0	2041	10

(Sources: European data from *European Alternative Fuels Observatory*. Other data from International Energy Agency's *Global EV Outlook* 2020.)

The **Scottish** Government pledged in its 2017 Programme for Government that they would phase-out “the need for new petrol and diesel cars and vans by 2032” by expanding charging infrastructure (Scottish Government, 2017). The Scottish Government does not have the powers to ban the sale of particular vehicles, as this is reserved to UK Government (Diamond, 2020).

In the UK as whole, a purchase grant for fully electric vehicles was reduced from £4,500 to £3,500 in 2018, to £3,000 in 2020 and £2,500 in 2021, while the grant of up to £2,500 for plug-in hybrid vehicles was ended in 2018 (HM Government, n.d; DfT, 2020). While these grants are available in Scotland, the Scottish Government also provide a 0% interest loan for the purchase of BEVs and PHEVs (although overall ULEVs currently comprise a slightly smaller proportion of the overall stock in Scotland than in the rest of the UK; Dodson et al., 2019).

In **France**, the 2017 Climate Plan pledged to end the sale of cars emitting GHGs by 2040 (Ministère de la Transition écologique et Solidaire, 2017). A ‘bonus-malus’ system exists, with subsidies available at different rates for different consumers of different vehicles, and a heightened tax on the most polluting vehicles. The 2016 ‘bonus écologique’ offered €6500 for a PHEV and €10,000 a full electric vehicle when replacing a diesel vehicle of 15-years or more by a new LEV. The eligibility criteria was lessened to 10-year old diesel vehicles in 2017 (Styczynski and Hughes, 2019). At the time of writing there were 867 passenger cars per EV charging point (EAFO, 2020).

The ICV phase-out date often referenced for **Germany** is 2030. This originates from the German Upper House (the Bundesrat) adopting a recommendation in 2016 that all new vehicles in the EU should be zero emission by 2030. Although this is thought to be an important policy signal it is a non-binding proposal, and currently not reflected in regulations (Gubman et al., 2016). German policy supporting LEVs initially focused on public-private investment programmes in R&D. From 2011 consumer incentives were also introduced, including tax exemptions for LEV commercial vehicles and a purchase grant of €4,000 for BEVs and €3,000 for PHEVs (extended to FCEVs in 2012) (Styczynski and Hughes, 2019). As part of a Covid-19 economic stimulus, the German government increased subsidies to €6,000 for BEVs and €4,500 for PHEVs in 2020. The close of the subsidy scheme was also extended from the end of 2020 to 2025, with its cost split evenly between the German automotive industry and the government (DW, 2020). At the time of writing there were 1,165 passenger cars per EV charging point (EAFO, 2020).

In the **Netherlands**, EV policy is distinctive in terms of the level of investment in public charge points, with the highest level of public charge points per capita of anywhere in the world (in 2017) (Hall and Lutsey, 2017). At the time of writing there were 150 passenger cars per EV charging point (EAFO, 2020). The Netherlands and Norway have by far the most public charging stations per capita (or per vehicle) in Europe (Hall and Lutsey, 2017), but Norway has a much larger share of EVs in the total passenger car population than the Netherlands (see Table 3). The Netherlands has one of the highest population densities in Europe and the spread of charging points has mainly taken place in cities, where on-property charging is less possible. The 2017 coalition agreement set out that by 2030 (at the latest) all new cars must be zero-emission (Dutch Coalition Government, 2017).

Instead of a phase-out date, the **Japanese** Government has set targets for the market share, as a percentage of total new vehicle registrations held by Next Generation Vehicles (NGVs). In 2010, the government launched the Next Generation Vehicles (NGVs) Strategy with targets for 50-70% market share for NGVs (BEVs, PHEVs, FCEVs and other hybrid vehicles) by 2030 with BEVS and PHEVs to make up 20-30%, but the majority to be hybrid (vehicles that cannot run on all-electric mode) and less than 3% to be FCEVs (Faivre and Lecler, 2014).

Japan is the second largest global producer of passenger vehicles (IEA, 2016b). The Council for Electrified Vehicle Society (CEVS) was launched in 2019 to promote collaboration and information sharing among the automotive industry and public sector. The Japanese government also released a Strategic Roadmap for Hydrogen and Fuel Cells in 2019 with a target to reduce the price difference between FCEVs and BEVs (IEA, 2020). Despite Japanese companies producing the best-selling FCEV models, and fuel cell technology having a role in Japanese domestic heating, FCEVs are only forecast to provide a negligible amount of future passenger vehicles in Japan. The Japanese Government provides subsidies up to 200 000 Yen (€1,600) for PHEVs, up to 400 000 Yen (€3,200) for BEVs and up to 2,250,000 Yen (€18,000) for FCEVs. PHEVs, BEVs, FCEVs are also exempt from various taxes (IEA, 2020).

Despite suggestions that ‘substantive’ policies to support EVs are not always in place prior to phase-out goals being set (Meckling and Nahm, 2019), many countries do offer support for LEVs via subsidies for consumers and sometimes producers. Styczynski and Hughes (2019) find the governments of China, USA, Japan, Germany and France (all countries with large existing automotive industries) use a “remarkably similar portfolio of policies” (p. 269), although levels of spending may be different.

Policies in **EU member states** that support automotive manufacturers to develop alternatives to ICVs is subject to ‘state aid’ restrictions, determined on a case-by-case basis (European Commission, 2014b). National automotive industries have, however, regularly received public support, and a collaborative €3.5 billion fund involving French and German carmakers to assist the development of battery manufacturing in Europe was approved at the end of 2019 (Espinoza and Chazan, 2019).

Low Emission Zones (LEZs) are increasingly common in urban areas around the world; there are now over 250 in the EU (Transport & Environment, 2019). Whilst their primary objective is the reduction of local air pollutants, including particulate matter (PM_{10} and $PM_{2.5}$) and Nitrogen Dioxide (NO_2), they also help to address GHG emission reduction targets. Historically, however, there has been a tension between local air pollution and GHG emission reduction. Diesel vehicles were promoted by many governments in the early 2000s due to their on average lower carbon dioxide (CO_2) emissions than petrol vehicles. As local air pollution became more of a concern and it was revealed that some manufacturers had been misreporting levels of NOx emissions from their diesel vehicles (‘Dieselgate’), policy support for diesel vehicles has been reduced or removed (Brand, 2016), although they remain a large part of the personal vehicle stock in many countries, including the UK.

LEZs exist in many countries and regions, with city authorities, for example in Paris and London, typically offering some form of compensation or incentive for businesses that have to switch to vehicles that conform to regulations. LEZs are designed to prohibit or penalise the most polluting vehicles entering a particular area. Zones often impose restrictions on public and commercially owned fleets i.e. buses, taxis etc., with the intention of imposing restrictions on wider vehicle fleets in the future. A review of the impacts of zoning in Europe found that German LEZs that restrict passenger cars as well as heavy duty vehicles recorded the biggest impact on local air pollutants (Holman et al., 2015).

Phasing-out ICVs requires policy focused on supporting **LEV charging infrastructure** – charging points and potentially electricity grid reinforcement. The infrastructural investment necessary to facilitate the widespread use of EVs is a feature of ICV phase-out policy in the countries considered. A key feature of demand side policy is to not only make EVs more attractive to purchase, but also to reduce the concerns that many users have with respect to their usability e.g. 'range anxiety'. The widespread installation of charge points represents a necessary commitment from public authorities. Without EV uptake these new infrastructures may become stranded assets, but without their existence large scale EV usage would be almost terminally inhibited. There are also many examples of private sector collaboration in charging infrastructure, with car manufacturers and electricity generators contributing to the cost of or simply building their own charging infrastructure; regularly updated databases of charging points are available[10].

4.2.2 Transport fuels

As global concern around climate change has risen biofuels have emerged as a possible means of reducing GHG emission from surface transport (Sperling and Gordon, 2009; Boucher, 2012a). Biofuels also offer possible security of supply benefits (being able to be sourced from a wider variety of locations than fossil fuels), and have potential to expand the markets for agricultural produce.

The use of transport biofuels in **the EU** was stimulated by the 2003 Biofuels Directive (Boucher, 2012a; 2012b). The Directive included a non-binding target of 2% biofuels in conventional transport fuel by 2005 and 5.75% by 2010 (Afionis and Stringer, 2012). The 2005 target was only achieved by three member states, and the 2010 target was amended in light of the developing technical assessment and politics of biofuels (Boucher, 2012a).

The enactment of the 2003 Directive led to much greater scrutiny of biofuels and their emission reduction potentials, and highlighted concerns over embodied emissions in their production and transportation, and 'food vs fuel' land use concerns. Boucher (2012a) suggested that the speed of technical development of biofuels outstripped scientific understanding, and that the *heterogeneity* of biofuels (in terms of their production process, feedstocks and their countries of origin), contrasted with the *homogeneity* of regulation (all forms were permitted by the 2003 Directive, without recognition of the variation in terms emission reduction and impacts on the existing land use).

A 'second generation' of biofuels sought to address the emerging controversies by focusing on feedstocks from waste and non-food crops. However, this approach faced challenges because of the limited amount of waste available and the persistent issue of land use change: non-food crops either displaced food crops, or were planted in

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[10] See, for example, https://supercharge.info/changes

previously uncultivated areas, with consequences in terms of biodiversity loss and the release of GHG emissions (Boucher, 2012a).

These developing controversies resulted in a variety of amendments to EU biofuel policy. The 2003 Directive did not impose strict sustainability standards, but the 2009 Renewable Energy Directive (RED) and Fuel Quality Directive introduced emission reduction and land use eligibility requirements (Stattman et al., 2018). The RED has a headline target of 20% of total energy to be met by renewables by 2020; the amount that biofuels could contribute was capped at 7% in 2015 (Stattman et al., 2018).

The Renewable Transport Fuel Obligation (RTFO) is a **UK** policy responding to the EU Directives. The RTFO was announced in 2005, came into effect in 2008 and originally required a 5% blend of biofuels with fossil transport fuels by 2010. Following the 2009 RED and more stringent sustainability criteria, the 2010 target was amended to 3.6% (Boucher, 2012a). Suppliers are required to either achieve this level from their overall supplies (rather than every delivery having to be the specified level, some could be less and some more), buy credits from other suppliers that had exceeded this level, or face a fine. In 2017, the RTFO required a 4.75% blend with petrol or diesel. Fuels derived from waste provide double credit, and this meant that the actual volume supplied conforming with the target was 3.3% by volume (or 2.6% by energy) (DfT, 2017a).

As the RED requires 10% of road transport fuel (by energy) to be from renewable sources in 2020, the RTFO was amended in April 2018. The main obligation is to be incrementally increased from 9.75% by volume in 2020 to 12.4% in 2032 (equating to 5.3% and 6.7% by energy) (DfT, 2017b; DfT, 2017a; DfT, 2018). The current European petrol fuel standard (EN228) permits fuel suppliers to supply petrol containing up to 10% ethanol (E10) and the diesel standard (EN590) allows up to 7% biodiesel in diesel (DfT, 2017b). Petrol in the UK is, however, typically currently E5 (no more than 5% ethanol) and diesel is no more than 3% biodiesel (DfT, 2017b).[11] Despite being sold in parts of the EU and elsewhere in the world, E10 is not widely available in the UK, and there are estimates that several hundred thousand older vehicles are not compatible with it (primarily vehicles built pre-2000, but also some others) (DfT, 2018)[12]. The move to E10 has been promoted for several years as a means of supporting the UK bioethanol industry (DfT, 2015). Other national markets have much higher levels of biofuels blended in transport fuel (for example, E27 is used in Brazil and B30 biodiesel in Indonesia).

Sweden has by far the greatest volume of biofuel use for surface transport in Europe (18% in 2018) (IEA, 2019). This has been achieved through the blending of biodiesel in standard diesel, some blending of bioethanol in petrol and the use of E85 (85% bioethanol and 15% fossil petrol). Biodiesel in Sweden is primarily hydrogenated vegetable oil (HVO), sometimes referred to as ’renewable diesel’ (USDA FAS, 2018b). Unlike more traditional biodiesels, such as Fatty Acid Methyl Ester (FAME), and bioethanol, HVO can replace its fossil equivalent without any modifications to vehicles or infrastructure (IEA, 2019). Bioethanol blended over a certain level can only be used in specific car engines, or in ‘flex-fuel’ vehicles (FFVs) (Sprei, 2018).

From 2020, the minimum level for biofuel blends is 4.2% for petrol and 21% for diesel (Bonde et al., 2019). Blended biodiesel is now the main contributor to biofuel use in Swedish road transport, the vast majority of which is HVO, with Sweden using a third of

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[11] In the UK the latest reporting period showed that the majority of the RTFO is achieved using biodiesel (58%), and bioethanol (39%) (DfT, 2019).

[12] A UK Government consultation on the use of E10 ran from March to April 2020; see: https://www.gov.uk/government/consultations/introducing-e10-petrol

the global supply of HVO (IEA, 2018a; Bonde et al., 2019). In recent years 85-90% of liquid biofuels used internationally have been imports (IEA, 2018a) and in 2017, 75% of Swedish biofuel supply was imported biodiesel (mainly HVO) (IEA, 2019). The Finnish bioenergy company Neste produces the majority of global HVO, with operations in the Netherlands, Finland and Singapore (USDA FAS, 2018b).

The market for FFVs in Sweden has been supported by a vehicle purchase subsidy and lower taxes on biofuels. The market grew in the early 2000s, peaking at 25% of new sales in 2008. The inclusion of certain diesel vehicles in the 'green' category (entitling them to a government incentive), falling fossil fuel prices (making FFVs less competitive) and the questionable environmental credentials of some biofuels lessened the popularity of FFVs, and they comprised only 5% of new sales in 2011 (Sprei, 2018). Large filling stations were obliged to provide at least one biofuel option from 2005 which predominantly resulted in bioethanol (E85) being made available (90% of biofuel pumps are E85, two-thirds of stations supply E85) (Sprei, 2018; IEA, 2019).

The production of bioethanol has a long history in **Brazil**. Blending of bioethanol in transport fuel has taken place since the 1930s, and since 1980 the standard fuel available in Brazil has been some degree of ethanol/petrol blend, initially as a 5% blend (Pousa et al., 2007). The Brazilian Government started the PROALCOOL programme in 1975 as a reaction to the oil crises, with high petrol prices coinciding with low sugar prices (the key feedstock) incentivising the wider production of ethanol (Sperling and Gordon, 2009). This programme encouraged the domestic production of bioethanol and the supply of vehicles that were compatible with ethanol blends. Brazil is thought to be uniquely able to produce ethanol that is economically competitive due to the low cost of sugar cane production and the abundance of fertile land (Sperling and Gordon, 2009). There are a wide variety of estimates as to the avoided emissions from Brazilian bioethanol, from a significant carbon capturing effect to emissions greater than fossil fuels (Macedo et al., 2008; Walter et al., 2011; Matsuda and Takeuchi, 2018).

In the 1980s the Brazilian government initially intended to replace petrol use with ethanol and an increasing number of ethanol powered vehicles were purchased (90% of vehicles sold in 1984 ran on ethanol). When oil prices fell and sugar prices rose in the mid-1980s, the supply of ethanol fell and some owners of ethanol vehicles were left without fuel; sales of ethanol-only vehicles essentially ended by the 1990s. Ethanol was still produced, however, and used as 20% blend in the standard fuel. Flex-fuel vehicle technology (largely developed in the USA) became popular, and by the early 2000s the majority of car sales were flex-fuel (Sperling and Gordon, 2009). FFVs do not run as efficiently on ethanol as an ethanol optimised vehicle, but can run on any blend of ethanol / petrol. The standard fuel in Brazil is currently E27 (USDA FAS, 2018a).

Since 2018, **Indonesia** has had a mandatory 20% biodiesel blend in diesel. In 2020, this increased to 30%. Biodiesel in Indonesia is Fatty Acid Methyl Ester (FAME) made from palm oil. Palm oil has a wide variety of uses including in food, chemical and fuel production. While Indonesia supplies roughly half of global palm oil trade, the domestic market for palm oil biodiesel has increased rapidly in recent years: in 2013 it exported more than it consumed, but by 2017 10 times more biodiesel was used domestically than exported. This change has largely been brought about by the sharp fall in demand for Indonesian biodiesel from the EU (ICCT, 2019b), given revisions to the sustainability criteria in EU biofuel policy and embedded emissions associated with Indonesian biodiesel (mainly resulting from land use changes). Most of the expansion in biodiesel production in Indonesia has involved the replacement of tropical forests with palm oil plantations (NNFCC, 2019). The increasing requirement for biodiesel blends across

Indonesia is partly instigated by falling export demand and a desire to find a new market for domestic production (Christina, 2019).

While new vehicles can be developed that are compatible with higher blends of biofuels, vehicle development cycles can be costly, and manufacturers often prefer clearly signalled step changes in blend limits than more gradual changes that require the development of multiple models (AEA, 2011). So-called ‘drop-in’ fuels, such as HVO (a type of biodiesel) can be blended at much higher levels with little or no impact on vehicle compatibility (as is the case in Sweden) (DfT, 2017b). Currently, UK biodiesel is 98.9% fatty acid methyl ester (FAME) and the rest is HVO (Ricardo Energy & Environment, 2018).

ICV phase-out goals often leave room for biofuels to be used in PHEVs, and this is currently permitted after the target phase-out dates of some countries, including China. (The inclusion of PHEVs is subject to wider criticism due to the uncertainty around their emission reduction potential.) The role of biofuels in the long term surface transport decarbonisation is likely to become limited in most countries. For example, the UK Committee on Climate Change recommended that the use of biofuels in surface transport be phased out in the 2030s, with the possible exception of heavy goods vehicles (CCC, 2018a; CCC, 2019a). In September 2017, the Chinese government announced a nationwide ethanol mandate that expands the mandatory use of E10 fuel from 11 trial provinces to the entire country by 2020 (OECD-FAO, 2018). This plan was, however, aborted at the last minute, in response to food security concerns (South China Morning Post, 2020).

4.3 Electricity sector

A fully decarbonised electricity supply is a key tenet of climate change policy. Although the precise mix of technologies in the net zero portfolio varies by context, coal, as a particularly carbon intense form of power, has been subject to early phase-out policy efforts in many countries. Nuclear power, although a contributor to low carbon electricity in some countries, has been subject to phase-out policy in many countries for reasons, including safety, waste management and public opposition concerns.

4.3.1 Coal phase-out policy

Over 30 nations pledged to phase-out coal fired electricity as part of the Powering Past Coal Alliance (PPCA) formed at the United Nations Conference of Parties (COP) in Bonn, 2017 (Blondeel et al., 2020). Many of these countries do not use coal in large quantities, if at all, with the largest consumer, Canada, accounting for 0.5% of global coal consumption, and as of July 2019, all members accounting for 3% of global consumption (Zhao and Alexandroff, 2019). According to Blondeel et al. (2020), the Alliance is an ‘external commitment device’ that helps countries that have already pledged to phase-out coal to avoid future policy reversal, by making a visible international statement of existing commitments.

One Alliance member, the **UK**, has seen coal use for electricity fall from nearly 100% of the generation mix in the 1950s, to 7% in 2017, with the last UK coal power station due to be closed in 2025 (Littlecott et al., 2018). Decline in the use of coal for electricity between 1950 and 2000 was driven largely by economic considerations, especially with the ‘dash for gas’ in the 1990s, but it also reflected longstanding political support for nuclear energy in the nationalised industry era. Coal fired electricity was initially fuelled by large scale domestic coal production, but this declined dramatically in the 1970s and ‘80s as a result of the reduction of government support (Parker and Surrey, 1995).

From the early 2000s, a range of European and UK regulations and policy instruments including the EU Large Combustion Plants Directive, the UK climate change levy (CCL) and the carbon price floor (CPF) meant that despite relatively high gas prices, coal generation continued to decline (Pearson and Watson, 2012). In 2015, the new Conservative government committed to the phase-out of unabated coal by 2025, and in 2020 this target was brought forward to 2024 (BEIS, 2020b). By October 2020, there were just four operational coal plants in the UK (Evans, 2020).

Some UK coal plants have been converted to run on biomass: the large Drax power station has already converted four of its six coal generating units to biomass and, after a High Court challenge by environmental group ClientEarth, plans for two new gas turbines were cancelled in favour of additional biomass units.[13] The UK is already largest consumer of biomass for power generation in the EU (USDA FAS, 2018b) and biomass generating units have government support until 2027 (CCC, 2018a).

Canada has generated between 10-20% of its electricity from coal since 1970. Currently, around 10% of Canadian electricity is supplied by 14 coal power plants (80% is from renewable sources, primarily hydroelectricity) (Govt. of Canada, 2018; PPCA, 2019). A decline in Canadian coal generation between 2000-2015 from 20% to around 10% was due largely to the province of **Ontario** phasing-out its coal plants between 2007 and 2014. Initially, this phase-out was planned between 2003-2007, but after it became apparent that this timeline would be challenging in terms of system reliability and cost, the deadline was moved to 2009 and then extended again to 2014 (Hrab and Fraser, 2010; Harris et al., 2015)

Coal provided 20% of Ontario’s electricity in 2007 (Hrab and Fraser, 2010), but all plants were State owned and relatively old when phase-out legislation was introduced. Health concerns were seen as the primary driver, rather than decarbonisation, with the Ontario Clean Air Alliance and Ontario Medical Alliance key advocacy groups (Harris et al., 2015). Alongside this, the phase-out was seen as complementary to the Green Energy and Green Economy Act that sought to develop green industry. Harris et al. (2015) suggest that the key lessons from Ontario’s phase-out include the need to clearly communicate the reason for change, to offer a ‘big picture plan’ about the replacement technology, and that “haste can be costly” – as an unachievable timeline is likely to lead to broken promises and delays; they conclude that a multi-party consensus and a broad advocacy base provides the necessary firm signal that phase-out will take place.

Another Canadian province, **Alberta**, has announced plans to phase-out coal power by 2030. The context here is different from that of Ontario in a number of ways. At the time of the phase-out announcement, coal provided two thirds of the province’s electricity demand. Alberta’s coal power stations are mainly privately owned, and the wider fossil fuels industry is also one of the province’s largest employers. Alongside this, smog and air pollution are lower in Alberta, and thus the more immediate health benefits of phase-out are less relevant (Vriens, 2018).

In a context more challenging for coal phase-out, the Albertan provincial government gained support from the affected power companies and workforces with pledges of compensation (to be funded from recycled industrial carbon taxes) (ibid). Cooperation was also aided by the anticipated conversion of almost all of the coal power stations to gas, which is cheaper and also commercially exploited in Alberta. These coal-to-gas

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[13] See https://www.bbc.co.uk/news/uk-england-york-north-yorkshire-56200100

conversions have shorter lifespans than new gas plants, and so are less likely to be impacted by future emission reduction policy.

The coal power companies have backed the plan, but the coal mining industry has not, and it is anticipated that much of the mining industry will disappear, with little prospect of it switching to export markets (ibid). Given the significant potential for opposition and future policy reversal, several preventative backstops have been introduced to inhibit policy roll-back. These include working with affected stakeholders, striking financial contracts with power companies, and issuing federal (Canada-wide) regulations on coal emissions. Ultimately, cheap natural gas plants would have likely led to the natural retirement of many coal power stations in Alberta, irrespective of the phase-out (Vriens, 2018).

Finland generated 10% of its electricity from coal plants in 2017 (IEA, 2018c). Coal is also used to provide heat via cogeneration or standalone district heating systems. Finland has very little domestic coal reserves and imports most of its supply from Russia. Coal phase-out policy in Finland involves the end of coal fired electricity generation and district heating by 2030. The aim is for coal power to be largely replaced with nuclear power, and coal DH with bioenergy DH. Due to the established nature of both these technologies in Finland, the decision has been generally welcomed (Lund, 2017). The decision to use nuclear power, a technology on the margins of many energy transitions in Europe, may reduce the renewable energy industrial benefits from Finland's transition, although by focusing on domestic strengths (in nuclear supply chains) there will be local economic benefit (Lund, 2017).

Germany joined the PPCA in September 2019, and it intends to eliminate coal consumption by 2038 (Zhao and Alexandroff, 2019) This date was recommended by a Government 'Coal Commission' in 2019 and is being entered into law[14]. In 2018, coal was responsible for about 37% of German power generation (DIW Berlin et al., 2019). Germany has moved from domestically producing most its coal requirements to being more import dependent in the last decade (Zhao and Alexandroff, 2019). Hard coal, which is used to produce 14% of power, is now almost entirely imported, with government support for the last hard coal mines ending in 2018 (BGR, 2018). Lignite power plants account for 23% of electricity generation and these are highly integrated with open cast mines near power plants, with almost all lignite for power still domestically mined. Lignite power is more polluting but has historically been cheaper than hard coal or gas generation.

A report from DIW Berlin describes the many implications of coal phase-out (DIW Berlin et al., 2019). As coal power is typically cheaper than gas in Germany, it crowds out less polluting gas generation, not only in Germany but also indirectly in the countries that Germany exports electricity to. As gas generation is more flexible than coal, a switch from coal to gas would allow greater penetration of intermittent renewables to the grid. With a surge in the EU carbon price between 2017-19, gas power has become more competitive with hard coal and lignite. Although the phase-out of nuclear power may require a continuing role for lignite in the short to medium term (Campion, 2019), it is thought that coal phase-out in Germany will have only a minor impact on wholesale electricity prices.

Coal phase-out has arrived later in Germany than in some neighbouring countries due to the political importance of the coal industry, and public funding support for coal-related jobs (Blondeel et al., 2020). Large scale subsidies for coal mining have existed since the

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[14] See https://www.bbc.co.uk/news/world-europe-51133534

global energy crises in the 1970s (Rentier et al., 2019). Phase-out by 2038 is thought not ambitious enough by some German NGOs, and seen by some as incompatible with global emission reduction targets (Zhao and Alexandroff, 2019). While an initial schedule for power plant closure is currently being determined, reviews are also planned for 2026 and 2029 to determine whether phase-out can be moved forward to 2035. The average age of existing plants is 35 years for lignite and 30 years for hard coal (DIW Berlin, 2019), though capital investment in coal plants should pay off after 20 years and 'adequate profits' made after 25 years. Billions of Euros of compensation are also being provided from the federal government to power plants owners (The Guardian, 2020).

According to Rentier et al. (2019) Germany's 'coordinated market economy' helps to explain the slower destabilisation of its coal industry than in the more 'liberalised market economy' of the UK; the authors go on to argue that although Germany's coordinated economy allows strategic support for low carbon technologies, the same institutional framework provides greater employment protection, and the need to seek consensus can slow down the energy transition (ibid.).

4.3.2 Nuclear phase-out policy

The phasing-out of nuclear power in **Germany** began in 2002 under a 'red-green' coalition government involving Social Democrats and the Green party), with complete phase-out targeted for 2022. In 2010, under a new centre-right government, there was a brief change of policy that extended the life of the existing plants, and would have seen complete phase-out delayed until after 2030. The original phase-out date of 2022 was, however, reinstated in 2011 in the wake of the Fukushima accident, with 8 German nuclear plants (of 17 in total) taken offline within 12 months (IEA, 2013). In 2002, Germany produced 28% of its electricity from nuclear, but by 2018 this had declined to 12% (AG Energiebilanzen, 2019). All decommissioned reactors were over 30 years old (Cherp et al., 2017).

Although there is a decades-long nuclear power industry in Germany, nuclear phase-out policy has met with less widespread public and political opposition than that seen for coal-power (Cherp et al., 2017; Rogge and Johnstone, 2017). The German coal industry – a direct competitor with nuclear for Germany's electricity baseload provision – has much better political representation than nuclear, and a large majority of the members of the German national parliament voted in favour of nuclear phase-out in 2011. (IEA, 2016c; Cherp et al., 2017). Post-war 'risk-consciousness' has also been seen to disadvantage the nuclear energy industry in Germany (Jasanoff and Kim, 2013).

The impact of nuclear phase-out in Germany on the diffusion of renewable electricity technologies is considered by Rogge and Johnstone (2017), via a survey of German renewable energy manufacturers and suppliers. They argue that nuclear phase-out policy has offered much greater support for renewable energy diffusion than other measures such as the EU-ETS and the Renewable Energy Source Act (which provides public funding support to renewables). The credibility that a phase-out date affords to the overall policy mix is seen as critical in facilitating increased private investment in renewable energy R&D. This effect was heightened at the time of the Fukushima nuclear accident, but has declined since. Rogge and Dütschke (2018) argue that nuclear phase-out policy in Germany is the most effective climate policy instrument, in terms of generating policy credibility for a renewables-based transition.

In the year prior to the Fukushima accident nuclear power supplied around 25% of electricity in **Japan**. This contribution had been removed entirely within 14 months of the accident, in 2012, and returned at only very low levels (1.7%) in 2016 (Suzuki, 2018;

Neidell et al., 2019). In 2012, the government introduced a policy to completely phase-out nuclear energy by 2030. In 2014, however, a new government abandoned a complete phase-out, while still pledging to reduce dependence on nuclear as much as possible. The Ministry of Economy, Trade and Industry has since suggested that nuclear power could provide 20-22% of electricity in 2030, not far from the pre-Fukushima level.

As of the end of 2018, 9 nuclear reactors were in operation (down from 39 pre-2011), while a further 6 have operating licences but are not currently running and 3 are under construction (Suzuki, 2018). Prior to Fukushima, there were government plans to increase the contribution of nuclear up to 50% of electricity supply. Japan has a large nuclear manufacturing industry, building many nuclear reactors overseas, supporting substantial employment and with powerful political support (Cherp et al., 2017). A further factor in Japan's reluctance to phase-out nuclear is that there are no significant indigenous resources of fossil fuels in Japan, so the country has no 'resource endowment' for heating (IEA, 2016b; Vivid Economics & Imperial College, 2017); Japan is among the largest net importers of oil products in the world (IEA, 2016b).

The 2012 shut down of nuclear power plants in Japan required the return to use of various mothballed fossil power plants (coal, gas and oil). This pushed up electricity prices between 10-40% in different regions (Neidell et al., 2019). Around half of Japanese residential heat comes from electricity, and the higher prices led to significant increases in cold-related mortality, with these effects arguably less tangible and salient to policy makers and the general public than the immediate effects of the Fukushima accident (ibid).

Reaction to the Fukushima accident was particularly strong in **South Korea**, given its proximity to Japan and its own reliance on nuclear power (which provided 29% of total generation in 2016) (Hong and Brook, 2018). In 2017, growing public concern resulted in the successful Presidential candidate pledging to phase-out nuclear power. Lim (2019) observes, however, that this phase-out is not straightforward or imminent, with nuclear capacity potentially increasing in the short term, as plants already under construction are completed. A South Korean citizens' assembly was used to decide whether two nuclear reactors that were already under construction (though less than 30% complete at the time of the election in 2017) should continue, with a narrow decision in favour of completion, but also with support expressed for phase-out over the longer term.

South Korean nuclear phase-out policy currently prohibits existing plants from applying for license extensions, but with the expected lifetime of plants currently under construction being around 60 years, full phase-out would not be achieved until 2080, leaving ample scope for policy reversal. The South Korean nuclear industry has in the past been guided by the state and viewed as crucial to national industrial advancement (Jasanoff and Kim, 2013). Further circumstances creating obstacles to rapid and full phase-out include continuing research into spent nuclear fuel management, partly for reasons of national defence (allowing South Korea to produce nuclear weapons more quickly if needed), given geopolitical tensions in the region (Lim, 2019).

Nuclear energy constituted about half of **Belgium**'s electricity supply between the 1990s and 2013. A phase-out policy has been in place since 2003 for seven existing nuclear plants; these were initially scheduled to be retired at the end of their economic lives, between 2015-2025. Government studies carried out shortly after 2003 had suggested prolonging the life of some plants, but in the wake of the Fukushima accident a new government (in 2012) rejected prolongation and elected to maintain the 2015-2025 schedule (Kunsch and Friesewinkel, 2014). In 2015, however, the three oldest plants were granted a stay of execution from 2015 to 2025 due to concerns over potential power supply shortages (IEA, 2016a; de Frutos Cachorro et al., 2019). All seven plants are now scheduled to be decommissioned between 2022-2025, with some ongoing concern about the electricity system's readiness for this change (IEA, 2016a; Reuters, 2019). The IEA anticipates Belgian nuclear supply to be replaced by a mix of natural gas, renewables and imports (IEA, 2016a).

In another decision heavily influenced by the Fukushima accident, in 2011 the **Swiss** Government announced its intention to phase-out nuclear energy. Five operational nuclear plants account for 35-40% of Swiss electricity generation (IEA, 2018b). Phase-out policy entails the prohibition of new nuclear plants or the lengthening of existing plant lifetimes, although existing plants can continue to operate if they remain safe (SFOE, 2018). With plant closure anticipated to come after 50 years of operation, decommissioning is anticipated to take place between 2019-2034 (Osorio and van Ackere, 2016). Despite being approved by parliament, the decision went to a public referendum (a common step in the Swiss policy process). This vote resulted in confirmation that no new nuclear licenses would be granted, although another vote that tried to limit the operating period of existing plants to 45 years was unsuccessful. The reactor at Mühleberg was the first to be shut down at the end of 2019, with the last forecast shut down at Leibstat in 2034 (World Nuclear Association, 2019).

While Switzerland has been net exporter of electricity, export levels have been falling and are expected to turn negative with the phase-out of nuclear power (IEA, 2018b). The Swiss Energy Strategy 2050 includes a number of future supply scenarios that involve different combinations of increased imports, improvements in energy efficiency, large increases in variable renewables and/or the use of combined cycle gas turbine power plants (SFOE, 2013)

5 Discussion

This section reflects on the international evidence base, and sets out how it can be used to help inform the effective design of phase-out policy in the heat sector. It first **summarises the evidence from different energy sectors** i.e. buildings, transport and electricity (sections 5.1 to 5.3). Each subsection reflects on the extent to which the sectoral evidence is analogous with the phase-out of fossil fuel heating, and the possible policy implications for heating. Following the sector specific insights, a number of **cross-sectoral themes** (5.4 – 5.8) are identified, and again, consideration given to the implications of these themes for fossil fuel heating.

5.1 Phase-out in the buildings sector

5.1.1 Evidence summary

This section brings together the cases of gas grids, condensing boilers and smart meters. As direct analogues for contemporary heat transitions – in terms of the energy service, the end users and industry involved – the gas grid and condensing boiler cases are often cited in heat decarbonisation studies. They are also two of the oldest cases considered in this review, allowing for reflection on the longer term consequences of policy initiatives – though this also means a greater difference in context. The age of the gas grid cases in particular, means that the institutional context (with contemporary energy markets more liberalised with a greater influence from private actors) is less similar than more recent cases such as smart meters.

The buildings sector cases incorporated a variety of **governance and economic arrangements**. While in the UK the gas network transition was state-led (with a private, sub-contracted workforce), the transition in the Netherlands was more ‘state-induced’, with shares in the new gas system held between the government and two large oil and gas companies, and with compensation for stakeholders in the previous system. Natural gas in the Netherlands was promoted by benchmarking the price to existing fuels (a practise that was common in many national energy sectors at the time), and offering lower costs for higher consumption.

The Dutch transition to high efficiency condensing boilers also involved a public-private collaboration, instigated and directed by state actors, in the form of the part state-owned gas transmission company and the national energy agency, with existing boiler manufacturers developing the new technology. A long and sustained period of policy support meant that a mandatory roll-out was not required.

The boiler transition in the UK took an initially similar form to the Dutch one, based on voluntary, subsidised take-up. In the UK, however, early market uptake was much slower than in the Netherlands. While technology diffusion rates are generally expected to be higher in later adopting countries (Wilson, 2012) a mandatory approach was deemed appropriate in the UK– by which time condensing boiler technology could be considered mature. The switch from supported to mandated change was made feasible by experience and learning from abroad, especially the Netherlands.

In the case of smart meters, regulated network operators are responsible for programme implementation and device ownership for almost all EU member states. In the UK, New Zealand and parts of Australia, energy supply companies have been given responsibility for roll-out. There is no consistency of programme outcome with designated responsibility: energy supply companies are now seen as an underperforming delivery body in the UK, but were judged effective in New Zealand.

Smart-meter implementation programmes have involved a mix of mandatory and voluntary approaches internationally. In countries such as Finland and Italy, a mandatory approach has proven relatively straightforward, with meters considered part of a system under the control of DNOs. In other countries (the UK, the Netherlands and Australia), a mandatory approach was initially adopted, only to be abandoned largely due to public acceptability concerns. There is also some variety in the details of programme design: the UK and the Netherlands cases saw different homeowner options for smart meter functionality (reflecting public concerns for data privacy), while in Sweden, meter *readings* rather than metering *technology* were mandated (allowing flexibility in how best to meet meter reading requirements).

Some countries have encountered significant issues with the **public acceptability** of smart meters, largely due to scepticism of the consumer benefit and data privacy concerns. In other countries, however, public opposition was less evident and privacy issues proved less salient. Consumer benefits were a common feature of smart meter CBAs across Europe, and most countries deemed smart meter roll-out to have a net present value for all consumers – with some exceptions, most notably Germany. This mixed public reception may reflect varied cultural contexts with respect to perceived civil liberties and privacy concerns. The distribution of the costs and benefits between multiple groups (consumers, suppliers and network operators) provides further opportunity for political and public opposition.

While the UK gas transition, perhaps inevitably, brought numerous consumer complaints, the programme as a whole encountered little resistance, reflecting high levels of trust between energy suppliers and households, and campaigns promoting the benefits of the new gas. The concurrent expansion in home central heating also helped to establish public acceptance. In the case of boiler replacement, despite the longstanding use of condensing boilers in the Netherlands, the UK saw significant levels of industry and consumer concerns about their introduction, and these concerns inhibited voluntary adoption for many years.

The widespread provision of natural gas heating in the Netherlands was predicated on **market and service expansion**, by attracting millions of smaller properties to join the new system. Previously, gas had been used only for cooking and hot water, but investment in an extensive infrastructure was deemed worthwhile because of the large anticipated additional revenue from buildings heating. In the UK, where gas was already partly used for heating, market expansion involved the proliferation of central heating, resulting in natural gas use vastly exceeding the peak town gas demand. In both cases, the transition resulted in an improved quality of life. By comparison, condensing boilers involved little market expansion and modest efficiency improvements (though these improvements helped to suppress rising energy bills).

5.1.2 Implications for fossil fuel heating phase-out policy

For new technologies with a wide possible range of functionalities, such as smart meters, there is a need to establish minimum performance standards. The EU sets minimum functionality requirements for smart meters but these leave scope for significant national variation. In several countries, including Italy, Sweden and the UK, second generation technology is replacing the first – demonstrating the potential for first generation **technology redundancy**.

The British and Dutch experience of gas grid re-purposing suggests that a wholesale change in heat infrastructure is technically possible (Eyre and Killip, 2019). Infrastructure repurposing in the UK and the Netherlands involves ongoing programmes with the replacement of the iron pipes in the low pressure gas distribution network with polyethylene or PVC pipes. These upgrades are, coincidentally, more suitable for carrying hydrogen and mean that suitable local distribution systems now exist and would require only relatively minor adjustments, in a similar way to natural gas conversions (Strbac et al., 2018; Sansom et al., 2019).

The high pressure national transmission pipeline system is, however, still made of steel and would have to undergo large scale conversion or replacement (Dodds and McDowall, 2013; Strbac et al., 2018). This is similar to the situation in the Netherlands in the 1960s, where the transmission system had to be built from scratch, whereas in the UK an existing backbone transmission pipeline was already in place (Correljé and Verbong, 2004; Arapostathis et al., 2019).

The prospective **governance arrangements** for heat decarbonisation vary according to existing forms of heat provision. For example, countries where gas grids provide a large amount of heat face different administrative challenges than those where gas grids play a minor role e.g. Finland. The scale of gas grid penetration is also relevant in terms of vested interests, as countries with more comprehensive grids will have greater sunk costs and stronger incumbent voices. For oil based heating provision, the effect of the incumbent industry is arguably lessened by the lower sunk costs involved.

British and Dutch gas grid re-purposing involved a central role for the state and the co-opting of incumbent interests in the form of the UK Area Boards and Dutch State Mines. Comparing key aspects of the 1960s gas transitions and the modern-day prospective transitions, Arapostathis et al. emphasise that much has changed in the UK gas industry since the vertically integrated control of the Gas Council. Today, the sector has disparate leadership involving numerous, privately-owned often multi-national companies with shorter planning horizons (Arapostathis, Laczay and Pearson, 2019, p.136). In addition, the Dutch approach to compensation helped smooth the politics of the natural gas transition, but is arguably currently overlooked in the UK given the uncertainty over heat decarbonisation pathways (Eyre and Killip, 2019; Rosenow and Lowes, 2020).

Mixed public responses to smart metering highlight the critical importance of consumer understanding of policy rationales, and the use of **mandatory or voluntary** policy approaches. Condensing boiler mandatory regulations in the UK were made in response to low early levels of uptake, despite clear benefits and minimal disruption. Given the urgency of Scottish and UK decarbonisation targets, the approach of a gradual voluntary phase-out (as seen in the Dutch condensing boiler case), or the gradual phasing-out of old technologies, as seen in Dutch and British smart meter programmes, is no longer tenable after a certain point. These pressures demonstrate the importance of clear and upfront communication of policy rationales – although even best practice public communications cannot guarantee public support.

By itself, heat decarbonisation is unlikely to bring about significant **market expansion** for heat services – the likely outcomes are similar service levels and potentially higher costs. While the widespread extent of energy poverty in Scotland and the UK suggests considerable scope for greater levels of heat consumption, thermal efficiency improvements, revised pricing and wider welfare policies arguably offer more appropriate means to address energy poverty concerns than the introduction of low carbon technologies.

The implications of **technological redundancy** become much greater as investment levels rise, with an out-of-date smart meter being much less consequential than a stranded heating system or network infrastructure. For heating transitions, early trials on isolated grids may be able to identify and mitigate against such risks.[15] Here, there is the potential for low carbon gas transition trials similar to those which occurred recently on the Isle of Man.

5.2 Phase-out in the transport sector

Phase-out policies associated with transport and heating decarbonisation are similar in a number of ways: both affect the daily lives of majority of the population, the envisaged changes will occur over a similar timeframe (from almost fully fossil fuel, to zero carbon within 20 - 30 years in many European countries), and they involve a similar range of technological options – electrification, biofuels and hydrogen. Although the ongoing nature of phase-out in transport means that it is often too early to evaluate the effectiveness of policies, compared to earlier gas grid and condensing boiler cases, these similarities invite reflection on the transferability of policy design and experience.

5.2.1 Evidence summary

The phase-out of ICVs is predicated on **the availability and affordability of replacement technologies**. Promoting LEVs involves a range of demand side financial incentives, including purchase subsidies and tax benefits, and non-financial incentives such as the development of new infrastructure and preferential use of existing infrastructure. In some cases, these incentives are becoming less generous, as technological progress has given governments growing confidence in the pace and direction of change.

In some contexts, demand-side incentives exist alongside **supply side policy**, particularly if an established national automotive industry exists. Supply side policy here includes manufacturer sales mandates (as seen in China and California), or R&D support (as seen in the EU). Some governments have also introduced ICV sales phase-out dates, although these are often aspirational targets, not yet normally legally binding, meant as a signal to manufacturers and consumers of a long-term policy intention. The automotive industry may value the clarity that these dates seek to provide, as well as the simplicity of a single point of change, as opposed to incremental multiple standards, as seen in, biofuel standards – although phase-out timeframes are unlikely to be universally accepted across a national automotive industry. Consumer groups may be initially alarmed by phase-out vehicle regulations, but the announcement of the date well in advance allows for the change to become normalised.

Public procurement is a common demand side policy instrument in ICV phase-out. National and regional governments often have large vehicle fleets, and it is common for these fleets to be subject to a mandatory minimum proportion of LEVs in new vehicle purchases; government vehicle fleets are set to be ‘zero emission’ by 2030 in the UK.

The Phase-in of LEVs is predicated on the development and roll-out of **new infrastructure** (such as public electric charging points, electricity grid reinforcement and storage infrastructure, or high blend biofuel provision). While all of the electric vehicle programmes reviewed here involved the roll-out of public charging points, there was no similar evidence of grid reinforcement for the specific purpose of EV charging. This may be due to the early stage of EV penetration in most countries and the more visible (and less disruptive) nature of charge point investments compared to grid strengthening, but it

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[15] For example, the Scottish Independent Undertakings (SIUs) are LNG and LPG grids supplying small towns in rural Scotland.

may also reflect uncertainty on the extent to which reinforcement is needed, alongside other options such as smart grid management.

The infrastructure changes needed to facilitate transition may lead to some challenges from the **co-existence of incumbent and emergent systems**. For example, while many BEV drivers are currently concerned with range anxiety and a lack of charge points, as ICV phase-out progresses an equivalent range anxiety may emerge for ICV owners as filling stations become scarcer, and the remaining owners of ICVs may need government policy support to ensure that they are not unduly disadvantaged by developments in the sector (see Rubeis *et al.*, 2019). Existing automotive manufacturers also face the challenge co-existing supply side assets, having to simultaneously wind down conventional vehicle plants and deploy the electric vehicle plants of the future.[16]

Transport biofuels are typically introduced as low blends, with higher blends restricted by **backwards compatibility issues** (for example, several hundred thousand vehicles in the UK are thought incompatible with E10 fuel). Concerns around the sustainability and emission reducing potential of biofuels also inhibit their promotion and growth. With car manufacturers and governments increasingly focused on the emerging EV industry, biofuels seem unlikely to provide a comprehensive solution to transport decarbonisation in most countries, and are more likely to play a role as a less disruptive interim option (and a means of powering more challenging vehicle types such as HGVs and aeroplanes)[17].

Although biofuels have thus far contributed much more to decarbonisation than electric vehicles in many countries, more ambitious energy and climate policy goals restrict scope for their continued use in passenger vehicles. For infrastructure technologies, a number of ‘network effects’ create new lock-ins and a focus on electric vehicles (and possibly hydrogen fuel cell vehicles) encourage learning and scale economies, improved performance, reliability and public acceptance. These heighten barriers to entry for alternatives and highlight the need for policy focus on the pace of Phase-in over time.

There is some ambiguity about the **scope and definition** of LEVs, and the role of transition technologies such as plug-in hybrid electric vehicles. The definition of LEVs has shifted over time in some jurisdictions; for example, the inclusion or exclusion of PHEVs in the UK. These changes draw criticism in some quarters, as hybrid vehicles recently purchased – the majority of LEVs in the UK – are likely to lose resale value. These shifts – and the mixed signals they may send to consumers – have been compared to shifting policies toward diesel vehicles (Wright and Rayner, 2020). While stability is valued in energy transition policies there should always be scope to adjust policy in light of a developing evidence base. More controversial or contestable changes are more permissible during certain windows of opportunity. For example, as climate change attracted more social protest, a more stringent target for ICV phasing-out arguably became more possible in the UK.

ICV phase-out is being accelerated by low emission zoning – a policy which has a **multiple benefit rationale**. The introduction of LEZs can be is seen as an indirect form of LEV policy support, as their primary objective is often reducing the concentration of local air pollutants rather than GHG emission reduction (see Section 5.6 for more on the overall rationale for policy). Although there are many reasons for ICV phase-out, the

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[16] See: https://www.theguardian.com/business/2020/dec/27/combustion-engine-car-factories-are-stranded-assets-in-age-of-electric

[17] See Chiaramonti et al., (2021) for a review of the contribution of biofuels in transport decarbonisation scenarios.

phase-in of EVs is increasingly facing scrutiny due to their much greater requirement for critical minerals such as Nickel, Cobalt and Lithium (IEA, 2021).

5.2.2 Implications for fossil fuel heating phase-out policy

Policies **promoting low carbon technologies** in the heat sector have some similarities to transport policy, but also important differences. While financial incentives are common in both sectors, non-financial, user prioritisation incentives, such as preferential access, seen in transport are absent in the heat sector. Supply side policy promoting new low carbon technologies is also less apparent in heating (see section 5.4. for in-depth discussion).

As in transport, **infrastructure change** is needed to facilitate a transition in heating. The type of infrastructure change – reinforcement, replacement or repurposing – is dictated by the choices over heat supply. Gas grid repurposing is an area-based process that also requires the modification of end-user appliances. The reinforcement of electricity grids, while also area-based, can be carried out in a more piecemeal fashion (and does not require end-user appliance modification). Ultimately, the extent to which the reinforcement of electricity distribution networks will facilitate heat electrification is key issue[18], with any heat decarbonisation pathway likely to involve a greater degree of infrastructure re-purposing or replacement than transport decarbonisation.

As in transport, the **co-existence of multiple technologies** (existing, hybrid and emergent) is apparent in heat decarbonisation. Given the investment costs and disruption involved with meeting peak heating demand from a fully electrified heat sector, hybrid heating technologies may offer a lower cost solution. For example, the CCC envisage a role for hybrid heat pumps using hydrogen if connected to the gas grid, or biofuels for energy inefficient off gas grid properties (CCC, 2018b, 2019).

There are also a number of questions and concerns about the use of **hybrid transitional technologies**. Hydrogen and biofuels both face uncertainties over supply sustainability, and hybrid systems that heavily rely on fuel rather than electricity could result in levels of embedded emissions which many be incompatible with net zero systems.[19] Price incentives could be used to encourage use of electricity rather than fuel in such circumstances. Hybrid heating systems may negate the need for electricity grid reinforcement, but they will also require the maintenance of both gas and electricity infrastructures, and while a hybrid heat pump may be cheaper than a stand-alone heat pump, it will at some point require reinvestment in two heating systems (boiler and heat pump) rather than just one. As seen in transport, declining or marginal technologies can face access and affordability problems. It is critical that these replication economies and network effects are included in heat decarbonisation analysis and policymaking.

The use of biofuels in transport and heating show some similarities, in terms of the **backwards compatibility challenges** of incorporating low carbon fuels in incumbent infrastructure. There is some uncertainty and debate over the appropriate blend-limit for transport biofuels, and different national and regional jurisdictions allow different levels. Similar regulatory issues are seen in heating (see section 5.7.2 for an in-depth discussion).

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[18] See Telford et al. (2018) for a Scotland-based analysis of this issue.

[19] Hydrogen, biodiesel and bio-LPG fuels all have embedded emissions (DECC, 2014a; Balcombe et al., 2018; BEIS, 2020).

There are obvious parallels in the role of **public procurement** for transport and heating. In heating, national and regional public authorities often have large building stocks using gas and oil boilers –technologies which have a similar lifetime to ICVs. For both sectors, mandatory procurement targets can be set. However, there is an important economic difference here: while the overall lifetime cost of LEVs is no greater than ICVs, renewable heating technologies are likely to be on average significantly more expensive over their lifetime than their fossil fuel based equivalents[20].

The **multiple benefits** policy rationale also plays out differently in heating and transport. Although heat decarbonisation will help to address local air quality issues, its role here is much less than transport decarbonisation. NOx emissions are mainly associated with transport (in the UK 31% of NOx emissions are from road transport and 14% from other transport, with only 4% arising from domestic combustion; DEFRA, 2020). Although domestic combustion is a much greater contributor to particulate matter (PM) emissions, accounting for 27% of PM10 and 44% PM2.5[21] this is almost entirely from burning wood in closed stoves and open fires (GLA, 2018; DEFRA, 2020). Rather than low air quality, heat decarbonisation policy is motivated primarily by international climate change efforts.

The historical experience of regulating transport biofuels offers a useful guide for challenges facing the heat sector. The first regulations governing transport biofuels in the EU did not take sufficient account of whole lifecycle sustainability issues. Phase-out policy should develop a comprehensive understanding of the possible implications of the replacement heating technologies and fuels, including possible unintended consequences, including fuel poverty concerns and possible changes to heating practices if heating services are made more (or less) expensive.

5.3 Phase-out in the electricity sector

Given their recent impact on emissions, technology phase-out experiences in the electricity sector are some of the most familiar to energy policy audiences. In contrast with the heat sector, however, changes in the electricity sector – especially the phasing-out of coal and nuclear power in some countries – have involved large scale and centralised operations that are removed from the day-to-day lives of householders. However, both electricity and heating involve complex decisions relating to infrastructure, and this, and similarities in political and institutional context, suggest that cross sectoral lessons can be drawn

5.3.1 Evidence summary

Conventional power plants often entail large sunk investments long technical or economic lifetimes. These characteristics raise **stranded asset risks**, and mean that technology phase-out may span several decades. As a result, the phase-out dates for coal and nuclear plants often extend beyond their economic lifetime (the point at which they are fully amortised). This creates potential for **policy reversal or delay**, and here, ‘external commitment devices’ such as the international Power Past Coal Alliance can help to embed policy.

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[20] In the CCC Sixth Carbon Budget (CCC, 2020), residential heating is modelled as having the greatest sectoral contribution to the overall cost of abatement (see Figure 5.6 in this report).
[21] Transport accounts for 13% and 14% for PM_{10} and $PM_{2.5}$ respectively (DEFRA, 2020).

Even so, some more ambitious or immediate power sector phase-out goals have been abandoned or delayed. This was seen, for example, in cancelled or postponed nuclear phase-out commitments made as a reaction to the Fukushima accident, in Japan, South Korea and Belgium. In other cases, where Fukushima-related phase-out commitments have not wavered, criticisms have arisen about the overall consequences, with, for example, Germany seeing increased overall carbon emissions. These experiences highlight the risks of optimism bias or misrepresentation in infrastructure planning, including on project costs and timescales (HM Treasury, 2013; Flyvbjerg, 2013; PAC, 2017; Lowes and Woodman, 2020); unanticipated cost escalations were also seen in the UK gas grid transition (Arapostathis et al., 2019).

Experiences in the power sector also highlight the role of **incumbent interests** as a critical factor in phase-out policy, with change likely to be challenged and undermined if it negatively affects those interests. The phase-out of coal in the UK involved a prolonged decline in the contribution of coal powered electricity generation and coal mining. These changes were largely driven by economic considerations: the availability of lower cost foreign coal and cheap natural gas, and a lack of political support for the coal sector after privatisation. In Germany, by contrast longstanding government intervention supporting and protecting coal mining has led to lock-in to coal-fired power, while the phase-out of coal in Ontario was in-part enabled by the absence of a native coal mining industry. In Japan – unlike Germany – a large scale nuclear manufacturing industry has resisted nuclear phase-out.

The availability of superior **replacement technologies** is also a critical factor: both Ontarian and Albertan coal plants are, at least partly, being replaced by natural gas plants, and this is also likely to be the case in Germany. Coal plants in Finland will be replaced with nuclear, an established technology that supplies the greatest proportion of Finnish electricity, and a number of countries phasing-out nuclear are also relying on natural gas replacement. Natural gas is often cheaper and always cleaner than coal, and the plants provide more flexibility and are much faster and easier to construct than nuclear. In all these cases, the replacement for the phase-out technology is attractive in ways over and above carbon emission considerations. In contrast, German nuclear electricity has been largely replaced by coal, frustrating decarbonisation commitments.

5.3.2 Implications for fossil fuel heating phase-out policy

Heat decarbonisation presents **stranded asset** risks for both infrastructure and end user technologies. Decisions on whether to continue to use gas grids will be heavily influenced by the degree of sunk investment. The British gas distribution network has been renewed in recent decades with the new pipes estimated to have a technical lifetime of 50-80 years (Dodds and McDowall, 2013). This ongoing renewal programme presents clear stranded asset issues, although the Committee on Climate Change has highlighted that the sunk costs of an extensive gas grid do not present an automatic case for infrastructure repurposing (CCC, 2018b; p.7).

Policy reversal or delay in some cases reviewed here, as the difficulty of technology phase-out becomes apparent, suggests the need for some caution in planning the phase-out of fossil fuel heat. The lifetime of heating systems can vary significantly (depending on usage regimes and maintenance levels), and there is also a difference between economic and technical lifetimes[22]. Domestic gas boilers are estimated as

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[22] The technical lifetime is the period over which the technology is able to fulfil its intended function. The economic lifetime is reached when by some form of economic calculation (a cost benefit analysis, net

having an economic lifetime of 12-15 years (BEIS, 2018c) while commercial scale boilers are likely to last much longer; around 25 years (CIBSE, 2014). Policymakers will naturally want to avoid the controversy of retiring private end user assets before the end of their economic lifetime. At the same time, mandatory phase-out dates cannot be set too close to the overall deadlines for achieving net zero, given the potential for installed systems to be technically operable well beyond their economic lifetime. The risk of overly optimistic costs and timeframes in infrastructural projects is also highly relevant here (Flyvbjerg, 2013) .

The **incumbent interests** associated with heat provision in the UK include a large number of small / micro enterprises that install and maintain end user systems, regulated organisations that maintain networks, suppliers of gas, oil and electricity and many others (Lowes et al., 2018). With the anticipation of phase-out, bodies representing these organisations will naturally lobby for transition paths allowing a significant ongoing role.

In terms of **replacement technologies**, all renewable and low carbon heat options present significant challenges, and there is no obvious ‘winning’ solution in the UK context, particularly with respect to properties on the gas grid. In the electricity sector, delays to initial phase-out dates were commonplace, even where a superior replacement technology was available. This suggests that technology phase-out in the heat sector – where replacement technologies are often inferior in some respects, and incumbent interest retain significant influence – may extend beyond envisaged timeframes.

5.4 Cross-sectoral issues: Supply side policy

5.4.1 Evidence summary

Transitions involving infrastructure technologies, such as mains gas and electricity, necessarily entail collaboration between the state and incumbent supply side actors. In transport, the transition from ICVs to LEVs is less reliant on infrastructure technologies, but still requires supply side policy directed at incumbent actors, and in countries with existing automotive industries, recent accelerations in transport transition policy are partly motivated by **industrial competition** and a desire to attain or retain a stake in future markets, with policies often developed in collaboration with existing manufacturers.

The importance of **industry-government alignment** in transport electrification is highlighted by private sector investment in charging infrastructure, pledges of phase-out among vehicle manufacturers, and industry contributions to vehicle purchase subsidies (Vaughn, 2017; Paton, 2020). Some major oil and gas companies have also expressed consent to accelerated ICV phase-out[23]. In the power sector, by contrast, a lack of consent from strong incumbent actors led to the rolling back of nuclear phase-out policy in Japan, while a broad coalition of support underpinned coal phase-out policies in Ontario and Alberta.

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present value calculation etc.) it is determined that it makes economic sense for the technology to be replaced (often by a more efficient alternative that has lower operational costs and that can ‘payback’ the upfront cost). Economic lifetime is often shorter than technical lifetime.

[23] For example, a recent announcement by Shell supporting the phase-out of ICVs by 2030 in the UK; see https://www.bloomberg.com/news/articles/2020-07-17/shell-says-u-k-can-bring-forward-gasoline-car-sale-ban-to-2030

Phase-out dates offer an important signal to both consumers and producers. In transport, ICV phase-out dates are intended to signal to the automotive industry that the decarbonisation of transport is embedded and that the investments in the next generation of vehicles (primarily electric) should follow. While these long-term signals are necessary to instil business confidence consumers may find the changes unsettling, given range anxiety or charging infrastructure concerns. Even so, long term phase-out dates in areas that directly affect end users are needed to raise awareness and engage public on the anticipated transition.

A range of additional **supply side incentives and mandates** are used. In China and California, mainstream car manufacturers are required to produce LEVs, and direct financial aid is also provided to some key Chinese manufacturers to help accelerate the transition away from conventional vehicles. The development of the condensing boiler in the Netherlands also involved a high level of supplier engagement, with existing boiler manufacturers invited by the Dutch national energy agency to develop a condensing boiler prototype. These supplier mandates encourage product design variety and innovation, particularly in the nascent stages of the market, as multiple suppliers compete for market share and attract consumers by catering to different tastes.

5.4.2 Implications for phase-out of fossil fuel heat

Industry-government alignment in the heat sector is frustrated by a lack of consensus over the sector’s net zero pathway. In the UK, where gas and oil boilers currently heat about 90% of domestic properties, incumbent gas and oil heating industries favour a continuity-based approach using technologies that build on their existing competencies and business models. Gas supply companies and distribution network operators support the re-purposing of the gas grid for the use of hydrogen (Lowes et al., 2018; Navigant and ENA, 2019), while bodies representing oil supplier and boiler installers favour biofuels (OFTEC, 2019). The principal low carbon alternatives to these options are technologies such as heat pumps and district heating, which currently only have a small stake in the existing UK heat sector but are well established in some other countries. As consensus on the preferable pathway may be difficult to establish, even among independent experts (Kattirtzi and Winskel, 2020), the breadth and strength of the advocacy bases for each option may be a critical factor.

Voluntary or mandatory arrangements between the state and supply side actors to develop new technologies are more feasible where the new technology shares some features with the existing technology e.g. ICVs and LEVs, and non-condensing and condensing boilers. Policy designed to promote **industrial competition** in heating may therefore be inclined to support the established capacities and interests of incumbent supply side actors. However, compared to personal transport, the lack of consensus on the heat transition path, and the greater variety of contexts and forms for heating technologies makes targeted supply side policy more difficult. The differing mixes of heating options internationally (and an absence of need for heat in some countries) mean there is less economic incentive in terms of global market pull. This said, hydrogen is likely to have an important international role in the decarbonisation of industry, and in home heating in some countries, and the early stages of heat industrial strategy can be found with the emergence of national hydrogen strategies in Germany and the Netherlands (Kerr and Winskel, 2020).

While fossil fuel heating **phase-out dates** are emerging for new buildings, the vast majority of the building stock that will be in place when net zero commitments are to be met is already standing, and it is the phase-out dates for these properties that are the most critical, and there are as yet few firm commitments here.

In terms of **supply side incentives and mandates**, policy that promotes technology design variety and innovation is essential in heating as a means of improving technological performance, but is arguably less relevant as a means of attracting new consumers than in transport, given the relatively inconspicuous nature of heating services and building energy use (Gram-Hanssen, 2014).

5.5 Cross-sectoral issues: Point of change

5.5.1 Evidence summary

The evidence reviewed here highlights different ways of designing the introduction of phase-out policy. **Trigger points** include the point of replacement (e.g. for non-condensing boilers in the UK), and the point of sale (e.g. transport proposals prohibiting the sale of new ICVs). New vehicles can be introduced alongside existing vehicles, so that a replacement trigger point is less salient in transport than in heating.

For both boilers and vehicles, the use of trigger points results in **uncertain and variable phase-out rates**. The application of phase-out regulations only to sales of *new* vehicles allows the continued use of existing ICVs, and in order to achieve national targets for net zero emissions, it is anticipated that some countries may have to introduce a hard end-date for the use of ICVs, alongside existing dates for the cessation of their sale. Current phase-out policy goals for ICVs are, however, typically not manifested in legislation, so act more as policy signals of changes that will eventually be necessary. As vehicle development cycles can be lengthy and expensive, the automotive industry may prefer phase-out dates that signal a **step change** as opposed to staged, incremental points of change. This can restrict, for example, higher levels of biofuel blending which would be incompatible with much of the car stock, and would require purposefully designed new vehicles, fuel-flex vehicles or drop-in biofuels.

Gas grid transitions must be coordinated across multiple end users in a defined area simultaneously. In such circumstances, with multiple technologies of variable ages, the point of change cannot occur at the end of the life of every existing technology unit – some degree of asset stranding is inevitable. In other areas, **freedom of consumer choice** may trump the economic benefits of co-ordination; for example, the phase-out of old energy meters in the UK has taken place on a unit-by-unit basis, despite evidence that programme efficiency is improved if it is coordinated on an area-wide basis by the regional DNO/DSO. The network operator is ordinarily the owner of the meter, with the exception of the UK, where new smart meters are now the ‘responsibility’ of energy suppliers. None of the smart meter programmes reviewed were designed around the lifetime of old energy meters. By contrast, many of the technology phase-outs that did not involve area-based change – condensing boilers, vehicles and power plants – were phased according to some definition of the existing technology’s lifetime.

In the electricity sector, there is a more formal, regulatory approach to phase-out. Here, points of change are often determined by the publication of a set of draft proposals and a formal consultation period, with the final arrangements depending on factors including overall decarbonisation targets and the suitability and readiness of alternative technologies. Phase-out dates for coal and nuclear plants were typically set at a late enough date for power plants to be, by some measure, beyond their **economic lifetime** (i.e. fully amortised).

There have also been **first mover** disadvantages for first-mover countries and early-adopter consumers. In Italy, the first country to introduce smart meters, the new technologies were soon outdated, with lower functionality than that subsequently required by EU performance standards, requiring a new roll-out programme. Early adopters of PHEVs in the UK (to date, the majority of EV owners) have found themselves facing shifting phase-out deadlines, with knock-on effects for their resale value and public trust.

5.5.2 Implications for fossil fuel heat phase-out policy

The appropriate **point of change** for the phase-out of fossil fuel heating depends on the replacement technology. The shift from natural gas to hydrogen requires an area based approach, meaning that some end-user disruption is inevitable (BEIS, 2018a). The early implementation of 'hydrogen ready' boilers and appliances[24] – with the same dimensions and connections as natural gas units – lessen the disruption involved, although there is some uncertainty over whether the existing internal domestic pipework may need to be replaced (Frazer-Nash Consultancy, 2018; BEIS, 2018b).

Switching from non-gas grid energy sources, or from gas grid to electric heating or biofuels would allow greater **choice for consumers** over the point of change. Although if adopted on a large-scale, electric heating would require reinforced electricity infrastructure i.e. the local distribution grid and possibly also a property's fuse rating. While the fuse rating could be upgraded at trigger points such as the replacement of the existing heating system, or a change of property ownership, any reinforcement of the electricity grid is likely to be carried out in an area-based approach.

Unless an area-based approach involves multiple technologies changing simultaneously, phase-out policy tends not to apply to technologies until the end of their **economic lifetime**. This is seen in the electricity sector, but also with point of replacement or point of sale triggers in transport and heating. If this is followed in heat decarbonisation, point of sale or point of replacement triggers will need to be applied in the 2020s to avoid prohibiting the use of private assets before they have achieved economic payback.

In the non-domestic sector, where boilers typically last for around 25 years, Scotland's 2045 net zero target means that a hard-end date for fossil fuel heating, alongside earlier trigger point(s), is likely to be required (CIBSE, 2014). The use of available economic levers is also critical here. Financial incentives and relative tax levels can be used to change comparative cost calculations, making low carbon heat the cost-effective option for end-users, while the capital and installation costs of new technologies can be reduced by public procurement and early Phase-in in particular contexts, such as new or public buildings.

Heating systems are analogous to vehicles in terms of their compatibility with biofuels and biofuel blends (see section 5.7.2). Much of the existing technology stock can only run on blends of a low level, with drop-in fuels providing an alternative, but this currently provides a very small fraction of overall supply. As a result, and given the short timescale for change, regulations in heat should enforce a **step change** in technology design, rather than incremental points of improvement to avoid the potentially costly design and implementation of multiple heating technology models that may be quickly outdated by revised standards. This needs to be clearly defined and explained to avoid loss of public support. When planning a step change, it may be attractive, at least initially, to allow continued use of less disruptive hybrid technologies (e.g. PHEVs in transport).

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[24] Dual fuel units that can run on natural gas or, after conversion, on hydrogen.

5.6 Cross-sectoral issues: Rationales for action

5.6.1 Evidence summary

The overall rationale for phase-out underpins the effective design and timing of policy and associated public and political support. Gas transitions in the UK and the Netherlands were motivated by the arrival of a **superior fuel**, in terms of cost, thermal capacity and toxicity. The prospect of a significantly improved energy service helped to legitimise the large scale infrastructure investment and upheaval involved. By contrast, condensing boilers offered only a relatively modest efficiency improvement over existing technology, but this also meant that there was minimal upheaval for suppliers and users. Smart metering is associated with a wide variety of potential benefits spread across the consumer and the supplier. However, the multiple rationales for smart meters are split between different actors, creating a principal-agent tension between who pays and who benefits – a tension that has led to public resistance of some implementation programmes.

In the transport sector, the recent development of phase-out plans for ICVs have been associated with emerging **industrial competition**. The development of the LEV industry is, however, ultimately founded on environmental and public health objectives, with industrial growth a secondary rationale for ICV phase-out, albeit one that supports the process. Global climate and local air pollution rationales can be mutually reinforcing in transport, but they can also be in tension: for example, petrol vehicles tend to have higher CO_2 emissions but lower local air pollutants than diesel vehicles.

The nuclear power phase-out programmes reviewed here were all heavily influenced by a single isolated event: the Fukushima accident in 2011. Particularly where it resonated with long-term anti-nuclear sentiments, Fukushima instigated a reactive form of policy-making that ultimately led to some later policy reversals (in Japan) or delays (in Belgium and South Korea). As discussed in section 5.3.1, the environmental rationale for coal phase-out has often been bolstered by a compelling **economic or technical case for alternatives**, in most cases natural gas.

5.6.2 Implications for the phase-out of fossil fuel heating

One key difference between the prospective phase-out of fossil fuel heating and the UK and Dutch gas transitions of the 1960s and '70s is that the **earlier transitions had a strong socio-economic rationale** that the current heat transition arguably lacks. Fossil-fuel heat phase-out also lacks direct salience for most consumers[25], and the public opposition to smart meters encountered in some countries illustrates the challenges in such situations.

With **industrial policy** helping to accelerate phase-out in some circumstances, the question arises as to whether fossil fuel heating phase-out could be advanced in a similar way. Pathways for low carbon heat are currently more diverse than those for transport, lending a less consolidated industrial policy rationale. The EV market is also global, while the market for low carbon (space/building) heat technologies is more

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[25] In recent surveys in the UK, while over 80% of people are concerned about climate change (BEIS, 2021), a similar proportion do not recognise home heating as a leading source of emissions (IMG, 2021). A recent analysis in Scotland concluded that concern about climate change is not driving the widespread uptake of low carbon heat (Caiger-Smith and Anaam, 2020)

localised, and mainly restricted to colder climates. The bioenergy market is also highly varied and complex, with multiple resources and possible uses, within and beyond heating and energy. Table 4 summarises the main differences in heating and transport fossil fuel phase-out.

Table 4: Comparative aspects of transport and heat decarbonisation

	Passenger vehicles	**Buildings heating systems**
Capital cost	Low carbon option more expensive	Low carbon option more expensive
Operational cost	Low carbon option less expensive, and overall lifetime costs are often cheaper	Heat pumps similar (if building is well-insulated); other electric heating options are more expensive. Hydrogen and biofuels likely to be more expensive.
Lifetime	Passenger cars have a lifetime of around 14 years (Fridstrøm and Østli, 2016; DfT, 2018)	Domestic boilers assumed to have a lifetime of 12-15 years (BEIS, 2018c). Non-domestic boilers around 25 years (CIBSE, 2014). Heat pumps are assumed to have a lifetime of 18 years (CCC, 2019b)
Performance	Very similar: vehicle range and re-charging time the main differences, with these are being reduced with technological development	Variable: low carbon gas and biofuel options can offer similar performance. Heat pumps offer lower temperature heat and potentially require longer operational times, larger heat emitters and/or fabric efficiency improvements
Technological similarity	Very similar: the only difference is the drivetrain (battery or internal combustion engine); other components essentially the same	Variable: low carbon gases and biofuels operate with similar technologies to fossil fuels. While some electric options offer significant technological divergence
Disruption for consumers	Low (although access to charge points is a major issue for many)	High (for many forms of low carbon buildings heating)

5.7 Cross-sectoral issues: Fuel phase-out

5.7.1 Evidence summary

Phase-out policies can apply to the technology, the fuel or to both. In transport, the policy of setting a final phase-out date is currently applied to vehicles, with fuels regulated to lower their carbon content (via biofuel blends) but not typically having phase-outs dates. As highlighted in Sections 5.2 and 5.6 there are **backwards compatibility issues** here – a so-called ‘blend wall’, although these limits can be stretched by the use of fuel-flex vehicles or ‘drop-in’ fuels such as HVO biodiesel. Cases where there has been large scale deployment of transport biofuels do not offer straightforward policy transfer experiences: Brazil is almost uniquely able to produce economic bioethanol; Sweden uses a very large proportion of global supply to meet its HVO needs; while Indonesian biodiesel is associated with deforestation.

ICV phase-out commitments that specify only full electric and/or fuel cell vehicles will effectively ban fossil or biofuel use in vehicle fleets. Most countries, however, have different policies and consents for different vehicle types, with larger, freight vehicles, shipping and aviation allowing continued use of transitional fuels (such as biofuels) in more challenging areas. Some jurisdictions currently include PHEVs in their consented passenger vehicles, allowing further opportunities for biofuel use. These hybrid vehicles may, however, have to be designed to be compatible with a high biofuel blend or be ‘fuel-flex’ in order to lower their emissions.

This continuity-based (low disruption) approach to transition policy is also seen in the power sector. In Alberta, most coal plants are to be converted to gas, while in the UK some coal plants have been re-purposed to be able to partly run on biomass. Coal-to-gas conversions and substitutions have been a means of gaining the support of incumbent industry for coal phase-out. Although they do not offer as large an immediate emission reduction as new, more efficient gas plants, they have shorter lifespans, with authorities and electric companies anticipating more stringent emission reduction targets in the future. (Biomass conversions in the UK have faced similar controversies to those faced by biofuels in transport, in terms of embedded emissions and impacts on land use.)

5.7.2 Implications for fossil fuel heat phase-out

Existing heating systems face similar **blending limits** as those faced in transport. It is thought that hydrogen can be blended into the UK gas grid with minimal requirement for modifications to the existing infrastructure and appliances at up to 7% by energy (20% by volume), offering emission reductions of 4-6%, depending on the method of production; blends higher than this would likely require infrastructure and appliance upgrades (CCC, 2018b).

Biofuels offer a possible route to emission reductions without requiring significant change in infrastructures or consumer behaviour, while also allowing existing stakeholders to broadly maintain their business model. Biomethane is a drop-in replacement for fossil gas (ADBA, 2020), but its contribution in the UK is thought to be restricted to about 4% of current supply, given limited availability of waste feedstock (CCC, 2016). A 30% blend of biodiesel in fossil kerosene heating oil (B30K) is thought to be compatible with modern boilers (i.e. those less than 5 years old) without modification; higher blends are likely to require a fully compatible biofuel boiler. Bio-LPG is considered a drop-in fuel, as it is chemically identical to LPG and can be combusted and stored using the same boiler and storage equipment (NNFCC, 2019).

However, the embodied carbon and land use change implications of biofuels are now better appreciated after the experience of biofuel use in the transport sector, meaning that large scale use of biofuel in heating is unlikely. In addition, biomass resources are scarce and may be prioritised for other uses. In the UK, the CCC suggest that biofuels should be phased out from surface transport in the 2030s, and reserved for use in thermal power plants with CCS (as BECCS), or in the production of hydrogen. Biofuels are therefore seen as having **niche or transitional roles** in UK heat decarbonisation – for example, as part of hybrid heating systems, with biomass boilers replaced with heat pumps by 2050 (CCC, 2018a; 2019).

The re-purposing of the gas grid from town/city gas in the UK and the Netherlands to natural gas are analogous with zero carbon heating transitions in terms of the grid infrastructure, but not fuel supply. Previous gas transitions were instigated by the emergence of a compelling, **superior fuel.** The current lack of a compelling alternative fuel to natural gas is arguably a more significant obstacle to heat decarbonisation than the engineering challenge of grid re-purposing.

The prospect of expanded hydrogen usage may be more analogous with the expansion of biofuel use in transport in the early 2000s, as a known fuel thought capable of addressing a new policy target with an upscaling of production. While their markedly different production processes mean that the limits on biofuel use will not necessarily be seen in hydrogen, they face similar embedded emissions concerns. This explains the long term focus on ‘green hydrogen’ production from electrolysis rather than steam methane reformation and CCS in emerging national hydrogen strategies (Kerr and Winskel, 2020).

5.8 Cross-sectoral issues: policy mixes and unintended consequences

5.8.1 Evidence summary

Policy must simultaneously promote phase-in – i.e. foster a viable alternative – alongside phase-out. Although Meckling and Nahm (2019) suggest that ICV phase-out may be introduced without substantive EV support policies, all of the cases considered here had substantial EV **incentive programmes** (financial and non-financial) in place before setting ICV phase-out dates. Similarly, financial incentives for condensing boilers preceded a mandatory phase-out date for non-condensing boilers in the UK. Coal phase-out has been effectively brought about by carbon pricing and emissions performance standards, meaning that the UK's 2025 end date now only applies to a limited amount of plants, all well beyond their economic payback times. The Dutch condensing boiler case and the ongoing transition to EVs in Norway further demonstrate that – where supportive conditions have existed for some time – bans are not necessary unless the pace of change needs to be accelerated to meet policy goals.

Policy driven phase-out should involve a period of scoping and impact assessment to identify potential **systemic and knock-on effects**. Inevitably, however, some impacts are not fully appreciated or anticipated at the time. For example, nuclear power phase-out in Germany has inadvertently led to a more carbon intensive electricity supply, undermining climate policy objectives. In Japan, the sudden phase-out of nuclear power in the wake of the Fukushima accident led to increased electricity prices and excess winter deaths. The increased use of biofuels in transport was associated with biodiversity loss and 'food vs fuel' land use controversies. While sustainability criteria for biofuels was tightened in light of these concerns, and second generation biofuels present less concern, competing land-uses (food, fuel, carbon sequestration etc.) mean that guaranteeing the sustainability of biofuel use on a large scale remains challenging internationally.

5.8.2 Implications for phase-out of fossil fuel heating

A range of **financial and tax incentives** can make low or zero emission heating systems more cost-effective, over their lifetime, than fossil heat. In the UK, however, financial incentives for renewable heating have not significantly altered its marginal status, with the relatively high level of tax on electricity and low level on gas a further barrier to change. UK and Scottish climate policies sit alongside fuel poverty reduction targets. With the overall cost of renewable heating likely to be more expensive than fossil heat, heat billing structures may need to be re-considered if decarbonisation is to avoid **negative effects** on fuel poverty commitments. A key issue here is relative tax levels on electricity and gas (the UK has a particular disparity between high electricity and low gas taxes; see Kerr and Winskel, 2020), but other questions include the extent to which upfront costs are to be socialised, levels of operational cost subsidy, and the heat as a service model for domestic consumers.

There are also opportunities for **end user segmentation** in heat policy. For example, some consumers may be more suited for the targeted early introduction of low carbon heat e.g. low temperature heat pumps are more feasible in new buildings built to higher energy efficiency standards. This could help to bring down costs and build up supply chains, before regulations are applied more widely at a later date.

Although **technological neutrality** is often held up as a policy aspiration (Helm, 2017) it is difficult to achieve in practice, and may not bring about innovation on the scale or pace required (Gross and Watson, 2015). None of the cases reviewed here could be said to reflect a purely technology-neutral policy approach: all required some specific infrastructural support, effectively making supply technological choices.

A technology neutral policy with the sole objective of cutting carbon emissions would ignore other policy objectives; for example, it may result in renewable heat technologies with low upfront costs but with high operational costs that exacerbate fuel poverty. A large scale move away from fossil fuel heating also has the potential to create systemic issues, for example, grid capacity issues associated with the widespread adoption of electric heating. Early adopters of biofuel heating may find a reasonably priced, sustainable supply, but due to changing activity in other sectors e.g. transport (aviation, maritime and land) and agriculture, supply may become constrained over time, inflating prices. In Belgium, technology neutral-based electricity decarbonisation led to the replacement of coal with biomass, with negative consequences for both resource sustainability and local pollution; see Carton (2016).

The difficulties of sustainably sourcing and processing transport biofuels are also seen in their use for heating. EU sustainability criteria mean that different biofuel applications compete for reduced supplies. In this context, there can be useful synergies between some biofuels (for example, production of HVO biodiesel for transportation can be adjusted to enable the co-production bio-propane / LPG for use as a drop-in replacement for fossil-LPG in heat or transport.

Although the sustainability and supply constraints faced by biofuels don’t map directly onto the hydrogen case, there is enough similarity to present a warning here, in terms of the need to take a systemic and full lifecycle perspective. While earlier gas transitions were essentially supply side led in response to the emergence of a superior fuel, the growth in biofuel use in the 2000s was – like contemporary heat decarbonisation – policy-led, in pursuit of environmental sustainability goals.

6 Summary and Conclusion

Historic analogues can inform uncertain and seemingly unprecedented policy challenges, and they are also valuable in communicating and engaging with stakeholders and wider public audiences. This report has analysed a wide range of energy sector technology phase-out policies and experiences that are analogous in some ways to the phasing-out of fossil fuel heating. Technological transitions ordinarily entail the simultaneous phasing-out of an existing technology or fuel and the phasing-in of an alternative, and the review has considered both the ‘destructive’ and ‘creative’ sides of energy sector transition policy making.

It is important to appreciate the differences between historic and contemporary transitions, as well as the similarities. Of the cases considered here, the 1960s town and city gas grid transitions in the UK and the Netherlands are analogous to prospective low carbon hydrogen transitions in terms of infrastructure re-purposing. The study of these earlier transitions provides useful insights in terms of regulation, organisational interests, market effects and the role of end-users. However, these earlier gas grid transitions are less similar to today’s heat policy challenge in terms of the economic and environmental characteristics of the fuel, the institutional context and the energy service impacts for end-users.

The more recent transition to condensing gas boilers offers a more institutionally comparable analogue with today’s heat challenge, but this transition involved much less disruptive technological change. The two national cases of boiler transition reviewed here differed in their timescales and agency: the Dutch boiler transition involved gradual, market-led uptake, led by a private-public partnership; in the UK, a mandatory regulated approach was used to accelerate uptake when a market-led approach proved too slow.

An ongoing case – the introduction of smart meters and the phasing-out of analogue meters – has also involved a mix of voluntary and mandatory approaches. Again, national experiences varied widely in this case, underlining the importance of policy choices and national context in defining phase-out experience. In the UK, the Netherlands and parts of Australia, a mandatory approach was abandoned due to privacy and public acceptance concerns. The case also highlights the need for trusted key organisations for programme management and user engagement, and importance of carefully presenting the rationales for policy-led change, and the impacts on consumers.

The review also considered experiences from other parts of the wider energy system, and despite some sectoral differences, partial analogues were again evident. The transport sector shows greater consensus on the transition path than heating, reflected in more developed policy and industry efforts, including ambitious phase-out dates for fossil fuel technology sales and significant private sector investment in low carbon technologies – although these efforts have yet to translate to significant emission reductions in the transport sector. The use of biofuels in transport and heating show many similarities, including concerns for backwards compatibility, resource sustainability and lifecycle emissions; and the long term role of biofuels in both sectors is likely to be restricted.

Technology phase-out in the electricity sector has progressed to a much greater extent than in transport or heating, but the experiences here have limited cross-over to heating challenges. In the UK, power sector phase-out has relied largely on supply side technology switching (away from coal towards gas and renewables), a process remote from most end users. The case also demonstrates the potential for delay or even reversal of policy-led phase-out. While accelerated and mandated approaches to heat technology phase-out may be necessary, given the pace and scale of policy goals, evidence from across multiple sectors suggests that an approach which results in widespread asset stranding could be vulnerable and subject to revisions in the face of industry and public opposition, or technical and economic barriers.

Finally, it is also important to consider overall policy rationales. Across all sectors, the more successful phase-out experiences reviewed here benefitted from multifaceted policy rationales and multiple benefits – economic, social and environmental. To the extent that it is mainly motivated by a single rationale – global climate change mitigation (though with other benefits in some situations) – heat technology-phase-out is particularly challenging. Heat technology phase-out as part of net zero policy will be less likely to suffer stakeholder, public and political opposition, and policy reversals, if the overall rationale for action is transparently evidence based, clearly communicated and widely understood.

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