INNOVATION & RESEARCH CAUCUS

ERC Enterprise Research Centre

UNDERSTANDING MISSION INNOVATION SYSTEMS

Framework and Case Studies

IRC Report 005

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Executive Summary

Aims and objectives

This report describes a new framework for understanding missions and their underlying mission innovation systems. It reports three UK case studies applying this new framework to missions (or potential missions) relating to domestic heat pumps, clean hydrogen and neodymium.

The key focus of the report is the development and validation of the framework for understanding missions. To this end, the case studies are intended to explore the value of the framework in different contexts rather than providing a comprehensive review of each of the case-study missions. This would require more extensive engagement than was possible here.

Definitions

- **Missions** - have been variously defined as ‘wicked’ problems or grand challenges or ‘purpose[ful]’ goals. Furthermore, missions may be either problem-focused (for instance, solving the problem of climate change but agnostic to the available solutions) or solution-focused (for instance, having identified heat pumps as a solution to address energy consumption, then focusing on the mission of implementation of the solution). Implementing missions may entail some form of scientific-technological break-through, especially when it comes to solution-implementation.

- **Mission innovation systems** (MIS) have been defined as ‘a temporary semi-coherent configuration of different innovation system structures that affect the development and diffusion of solutions to a mission that is defined and governed by a mission arena of different stakeholders’.

This emphasises that mission success will result from a complex set of interactions between system participants, including businesses, universities, and other actors. Individual mission contributions cannot be considered in isolation, but only in how they relate to other mission components of a collective structure of information formation and use. Through its role in shaping policy, regulations and incentives government can play a key role in ensuring the effectiveness of mission innovation systems.

Understanding Missions and MISs

Our approach to understanding mission development is based around the notion of ‘episodes’ during which different private and public sector actors and opinion formers play different roles. We identify five potential episodes in each mission: ideation, legitimation, implementation, completion, and retrospection.

- **Ideation –** which involves the formulation of possible mission objectives, timelines, and nature of the mission challenge. This provides the basis for discussion of objectives and approaches in the subsequent legitimation stage. Public sector actors are likely to be important in this episode in providing the evidence base on which mission ideation can be based. Private sector actors and citizens/end-users will be important identifying the variety of technical solutions which might be available to address mission objectives and identifying those options which are acceptable to the general population.

- **Legitimation –** this episode leads finally to agreement on mission objectives, timelines, scope, and stakeholder roles. The key activity here is discussion and consultation among stakeholders which is likely to be facilitated by public sector actors. Goals and roles may be strongly contested but coherence of stakeholder objectives is likely to be critical to mission success.

- **Implementation –** the working out of stakeholder roles and co-ordinated actions. This is the key functional and delivery stage of the mission and is likely to be the longest in terms of duration. Within the implementation stage sub-stages may be distinguished during which the roles of different actors change or vary in importance. Public sector actors will here provide support for solution development, shape the regulatory climate and co-ordinate joint and collaborative action. Private sector actors will contribute entrepreneurial and innovative inputs and consider how their other activities can be aligned with mission objectives.

- **Completion -** missions may be timebound and success may be full or partial. Public sector roles here are likely to involve monitoring and evaluation of outcomes.

- **Retrospection** - consultation and the capture of learning from missions. The role here is to feedback into improved mission innovation system (MIS) operations in future. The public sector's role would be to co-ordinate and convene. Private sector input may inform future actions.

Within each episode we focus on the different roles played by different actors – those in the public sector, private sector businesses, citizens/end-users, and intermediaries/community leaders/influencers. We anticipate, for example, that public sector actors may be more important in early phases of missions (ideation, legitimation) but the business sector and other actors may be more significant in the implementation phase.

We propose a two-stage research approach focusing first on surfacing the structure and actors within each mission before a more detailed, interview-based examination focused on identifying the role of different actors and related external constraints in each episode.

Domestic Heat pumps

The importance and validity (legitimation) of the heat pump mission and objective is widely shared among stakeholders. There remains less consensus on the viability of the specific mission target (an installation target of 600,000 pa by 2028), how this can be achieved, and what should be the development priorities.

Our interviews emphasised that heat pumps remain relatively expensive to buy and install and require additional investments in insulation, doors and windows, and sometimes electrical systems.

Long wait times for delivery highlight the urgency of addressing supply side constraints. However, supply side constraints were not considered the most significant chokepoint for heat pumps. Neither did participants agree that greater scale would reduce costs. Challenges with too few skilled people are available to install heat pumps were also widely reported.

Participants stressed making installation easier through designing “plug and play” systems. Overcoming acceptance challenges around the way we experience home heating also seem important. At the present rate the installation of domestic heat pumps is widely seen as unlikely to hit long term installation targets.

The application of the MIS framework to domestic heat pumps highlighted the complex inter-dependencies and diverse range of stakeholders involved in the mission, many of which have different views on future priorities. Legitimation of mission targets is limited, suggesting the importance of a more strongly evidence-based approaches to setting objectives.

Clean Hydrogen

The Clean Hydrogen mission, to which the UK is a signatory, launched in 2021 and aims to increase the cost competitiveness of clean hydrogen by reducing end-to-end costs to 2 USD/kg by 2030. There is widespread agreement that hydrogen cost reduction is important, but our conversations indicate that the mission is not currently a key driver of cost reduction efforts. There are also divergent opinions about whether a cost reduction mission is the right place to start, and if the target is realistically achievable in currently defined timeframes.

While the government is committed to the initiative and target in international forums, and is working towards fulfilling its obligations to the partnership through the publication of the hydrogen strategy, there does not yet appear to be a clear or joined up domestic strategy about how cost reduction should be accomplished. Also, there does not seem to be a clear imperative or division of labour between government departments that might control levers to affect mission success and, as a result, the coordination function important to the legitimation and implementation phases is largely absent.

The mission may increase in relevance/importance in line with the roadmap for consumer awareness initiatives (2028-2030) and as cross-cutting hydrogen initiatives - such as the Hydrogen Champion - begin to shape narratives and affect behavioural change. In this sense, setting, communicating and coordinating the time component of the mission (i.e. achieving cost reductions by 2030) is at least as important as the $2/kg metric itself.

As in the heat pumps case study, the MIS framework highlighted the complexity of the stakeholder community involved in the hydrogen mission. The case study also illustrates the challenges of translating internationally agreed targets into coherent domestic strategies, particularly where leadership and coordination responsibilities are divided. Policy is evolving rapidly in this area, and recent changes may encourage wider understanding and consensus around cost reduction targets. The potential for internationally agreed mission targets to become important particularly relating to climate change suggests a direction for future development of our initial framework.

Neodymium

Neodymium is one of the group of rare earths which are seen as critical to the net zero transition. International markets in raw materials and permanent magnets using neodymium are dominated by China, prompting security and supply chain concerns across Europe.

Along with other rare earths, neodymium has been the focus of recent policy development in the EU and UK. In 2023, the EU unveiled a proposal for its Critical Raw Materials Act (CRMA) for which the bloc secured a provisional agreement in November 2023. In July 2022 the first UK Critical Minerals Strategy (CMS) ‘Resilience for the future’ was published “to mitigate risks and to improve resilience of critical mineral supply chains” (BEIS 2022). An update on the strategy (March 2023) cites a number of developments including significant new investments in research and demonstration facilities, e.g. the Circular Critical Materials Supply Chains (CLIMATES) fund.

There are currently no established targets, objectives or any UK innovation mission relating to neodymium. The imperative for a potential UK mission focused on neodymium metal magnets finds unanimous support among interviewees, who identify two key drivers for such a mission: (i) the pivotal role neodymium magnets play in the UK's digital and green transitions, and (ii) the geopolitical implications associated with China's status as the dominant global producer of magnets.

Thinking about any mission relating to neodymium (and potentially other rare earths) remains very much at the ideation stage although having wide support (as in the heat pump and hydrogen cases). Any mission here is likely to be strongly problem-focused (i.e., the issues are clear, but the technological solutions are uncertain), and so engagement with the Science, Technology and Innovation (STI) system will be important. It remains less obvious who in government should or could catalyse any related mission.

Lessons for mission innovation policy

Recent research has argued that the “perceived time urgency” and “potential big impact” which characterize mission-innovation systems differentiate them from routine policy interventions. This assertion is at least questionable. Certainly, MIS will tend to be atypically large, complex, and potentially extremely impactful, but it can be argued, with some authority, that these are reasons to follow established best practice in policy development (e.g., ROAMEF) rather than adopt any new unproven approach. However, developing and delivering innovation missions is likely to require contributions from diverse stakeholders in all episodes from ideation to mission completion and retrospection (see Figure below). The need to engage diverse stakeholders in each episode shifts the focus of public policy making towards an emphasis on convening stakeholders, curating knowledge availability, searching for consensus, and building regulatory and incentive structures which can enable innovation. None of this is easy, however, as our mission studies amply illustrate.

The case studies do little to negate the need for adherence to established best practice in policy making. Indeed, in many ways they reinforce the need for rigour. This suggests:

- ***The importance of evidence-based policy making*** - The case studies highlight the importance of the evidence-based in setting targets, timelines and resource requirements.

- ***The bigger picture*** - Individual missions tend to be one element of a wider programme of policy measures. Targeted policy development needs to be fully contextualised within this wider programme.
- ***Setting realistic and achievable objectives*** - Policymakers seeking to address missions, such as those considered here, face pressures to set objectives that fully address the social need or align with international standards. However, in practice, there may well be a divergence between these requirements and what is realistic and/or achievable.

- ***Dealing with complexity*** - MIS tend to be highly complex and difficult to manage. This suggests the value of identifying policy options (e.g., regulation) which negate the need for management *per se*.

- ***Monitoring and evaluation*** - Best practice suggests that monitoring and evaluation should be included in all policy development. The nature of MIS highlights the importance of clear roadmaps in any future missions.

Applying ROAMEF to mission development and delivery

<table>
<tr><th></th><th>Ideation</th><th>Legitimation</th><th>Implementation</th><th>Completion</th><th>Retrospection</th></tr>
<tr><td>Activities</td><td>Formulation of mission objectives, timelines, and nature of challenge,
Provides basis for discussion of objectives and approaches</td><td>Discussion and consultation among stakeholders.
Agreement on mission objectives, timelines, scope, and stakeholder roles.</td><td>Working out of stakeholder roles and co-ordinated action.
Progress towards mission objectives.</td><td>Mission success – full or partial.</td><td>Consultation and capture of learning from mission.
Feedback into improved MIS operations</td></tr>
<tr><td>Rationale</td><td colspan="2" rowspan="3">Public sector – define challenge and evidence base, convening, seek to resolve contested issues and build consensus
Private sector – identify solutions and stakeholders, support mission definition, surface supply chain conflicts
End-users – contribute to problem identification, identify and agree acceptable solutions and ways forwards
Intermediaries- leadership and role modelling for user-led innovation, advocacy, mediation and bridging for contested issues</td><td></td><td></td><td></td></tr>
<tr><td>Objectives</td><td></td><td></td><td></td></tr>
<tr><td>Appraisal</td><td></td><td></td><td></td></tr>
<tr><td>Monitoring</td><td></td><td></td><td colspan="2" rowspan="2">Public sector– set regulatory and incentive structures, knowledge co-ordination and governance, monitor and measure progress
Private – entrepreneurial/innovative input to mission objectives, align activities with mission objectives
End-users – learn to adopt new behaviours/technologies associated with emerging solutions
Intermediaries – knowledge dissemination and education, role modelling of behaviour change</td><td></td></tr>
<tr><td>Evaluation</td><td></td><td></td><td></td></tr>
<tr><td>Feedback</td><td></td><td></td><td></td><td></td><td>Public sector – consultation and capture of learning
Private/End-users – sharing experience of what did and didn't work, adoption of lessons from mission delivery
Intermediaries – knowledge integration and dissemination</td></tr>
</table>

Lessons for understanding MIS

- Perhaps the first key lesson is the extent to which ‘missions’ are socially constructed initiatives, involving (at least ideally) agreement between organisations and individuals as to the targets, timelines, and boundaries of the mission. International targets with little clear ‘ownership’ or buy-in also complicate missions. Both place substantial demands on those convening organisations and individuals during the ideation phase of any mission and on their ability to mediate different perspectives and achieve even partial agreement. Understanding missions requires an understanding of the motivations and capacities of these convening organisations during the ideation phase.

- Second, evolution in our thinking during this first MIS study has emphasized the value of the type of semi-structured interviews which formed our key empirical approach. Generally, these worked well, allowing respondents to provide detailed and highly personalized perspectives. In future studies, discussion guides can be developed to reflect our analytical framework (built around episodes) more formally. Interviews with individual actors may also be usefully supported by focus groups with different stakeholder groups.

- Thirdly, any account of a MIS such as that provided here, necessarily provides a snapshot at a particular point in time. In terms of heat pumps, we are in 2024 in the ‘implementation’ phase relative to the 2028 installation target. ‘Completion’ and ‘retrospection’ are still to come. In terms of hydrogen and neodymium, we are earlier yet in the MIS cycle. This suggests the potential value of a longitudinal approach which can capture the changing roles and interactions between actors as missions develop and move towards completion.

- Finally, it is important to recognize that missions do not take place in isolation from the broader social and economic landscape. Even where mission actors agree and work in unison, therefore, outside circumstances may frustrate mission success. These wider conditionalities will need to be part of any future MIS analysis.

Section 1: Understanding 'missions' and 'mission innovation systems'

1.1 Introduction

This Section introduces the notions of innovation missions, and MIS. It builds on the few prior studies of MIS to develop a new conceptualisation of the development of MIS. This is based on the notion of 'episodes' during which different private and public sector actors and influential opinion formers play different roles as missions move from ideation, through legitimation towards implementation. This conceptual framework forms the basis for our approach to understanding the development of MIS and the case studies reported later in this report.

Discussion makes clear the potential role for government and public agencies in shaping relevant missions and at the same time the inherent difficulty of co-ordinating diverse actors around a single goal.

1.2 Defining missions

To understand MIS, it is important to first understand what is meant by the term "missions". Missions have been variously defined as 'wicked' problems (Wesseling & Mejerhof, 2021) grand challenges (Agarwal, Kim & Moeen, 2021) or 'purpose[ful]' goals (Stubbs, Dahlmann & Raven, 2022). Furthermore, missions may be either 'problem-focused' (for instance, solving the problem of climate change but agnostic to the available solutions) or 'solution-focused' (for instance, having identified heat pumps as a solution to address energy consumption, then focusing on the mission of implementation of the solution). And, while it is acknowledged that solving the problem may entail some form of scientific-technological break-through, especially when it comes to solution-implementation, running these solution-focused missions requires effectively leveraging the socio-institutional wherewithal (Wittman, Hufnagl, Lindner; Roth & Edler, 2021).

Given the grand socio-institutional nature of the impacts of missions (irrespective of whether these are problem-focused, or solution-focused missions), it is no surprise that researchers have argued that the associated MIS are characterized by "wickedness, temporality, embeddedness and transformative directionality of missions" (Wesseling & Meijerhof 2021). The inherent 'wickedness' of these purpose-driven missions as well as their 'transformative' potential, means that naturally these missions are found to be 'ambitious, exploratory, and ground-breaking in nature', and often require 'cross-disciplinary' knowledge exchange and coordination (Wittman, et al, 2021). Furthermore, the 'wickedness' emanates not only from the cross-disciplinary technological complexity but also from the implementation challenges which require shaping and incentivising social, institutional, and individual behavioural change (Wittman, et al, 2021).

Moreover, 'temporality' is found to be another fundamental characteristic of these missions exhibiting varying degrees of 'time urgency' in terms of responsiveness ranging from immediately/proximally urgent, for instance, vaccine development for COVID (as well as responding to the 'climate emergency') to more long-term focused missions like, for example, development of nanotechnology (see Agarwal, Kim & Moeen, 2021 for numerous examples ranging from development of radar technology development as a response to urgent military need during World War II to the more proactive, long-drawn focus of the human genome project).

Last but not least, missions are characterised by either failures or limitations inherent in market-driven mechanisms and incentives, consequently creating a 'public sector unmet need' and thus making it imperative for public-sector and governmental sectors to play a pivotal coordinating role in helping navigate the 'directionality' imperative. For instance, the United Nations Sustainable Development goals have been argued to provide such 'directionality' in terms of mission goal setting (albeit the UN plays a limited role in "coordination") (Stubbs, Dahlmann & Raven, 2022).

In summary, notwithstanding the different definitions and conceptualizations that exist vis-à-vis what constitutes a mission, 'wickedness', 'temporality' and 'directionality' (as found in Wesseling & Meijerhof's 2021 definition) are the three foundational components that seem to aptly encapsulate both the opportunities and challenges associated with the 'missions' on which various MIS tend to focus.

1.3 Understanding MIS

While the broad notion of mission-oriented innovation as focused on a particular grand challenge or mission is relatively straightforward, the effective implementation of this type of policy remains in its infancy. Although promising, missions remain understudied in practice, and a deeper understanding is needed of the innovation dynamics produced by missions and supportive governance actions so that more effective policy and governance interventions can be designed (Janssen et al., 2021). This has led to calls for the adoption of an MIS perspective (Hekkert et al. 2020). One recent contribution, reflecting the directional and transformational nature of mission-oriented innovation suggests that an MIS should be defined as: 'a temporary semi-coherent configuration of different innovation system structures that affect the development and diffusion of solutions to a mission that is defined and governed by a mission arena of different stakeholders' (Wesseling and Meijerhof, 2021, p. 2).

The definition of an MIS suggested by Wesseling and Meijerhof (2021) emphasizes the different 'innovation system structures' involved. This differentiates MIS from other, better understood, types of sectoral, regional, and national innovation systems. The notion of a national innovation system, for example, was initially introduced by Freeman (1982, 1987) and summarised by Metcalfe (1995, p. 38) as the:

> *'Set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such, it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts, which define new technologies'.*

This emphasises that innovation and technological progress results from a complex set of interactions between system participants, including businesses, universities, and government research institutes

(Freeman, 1995; Lundvall, 1992; Lundvall, 2007; Nelson and Winter, 1993; Godin, 2009). This suggests that 'individual institutions' contributions cannot be considered in isolation, but rather in terms of how they communicate with each other as components of a collective structure of information formation and use and how they interact with social institutions (e.g., principles, standards, legal frameworks)' (OECD, 1999 p. 24). Through its role in shaping policy, regulations and incentives government can play a key role in ensuring the effectiveness of national innovation systems.

So, what characterises a strong innovation system? In the context of national innovation systems, Edquist (2004) has suggested three criteria which must be met if an innovation 'system' is to be said to exist. These are likely to apply equally to a MIS:

- **Unified function** - an innovation system has a function, i.e., it has identifiable objectives or aims to which all elements of the system contribute. This might be evident in social partnerships (either formal or informal), agreed objectives and vision.

- **Coherence** - an innovation system will exist when the array of organisations and their relationships in a region or nation form a coherent whole, which has properties different from the properties of the constituents. In other words, we would expect to identify feedback systems or loops, common developmental trajectories, and complementary competencies between agents.

- **Bounded** - it must be possible to discriminate between the system and the rest of the world, i.e., it must be possible to identify the boundaries of the system. This could be geographic but may also be sectoral or technologically based.

Discussion of the effectiveness of national, regional, and technological innovation systems has adopted three main approaches focused on organisational capabilities, system functions and, more recently, pathways. Capabilities approaches focus on the capabilities of individual organisations within the system, e.g., the absorptive capacity of firms, and research capacity within universities. A functional approach emphasises system governance and operational capabilities, identifying key actors and their interactions (Roper et al. 2006). A more recent approach focuses on pathways through the system suggesting, as Shaw and Allen (2015, p. 88) suggest that 'pathways convey material and informational resources, as well as value like the nutrient and energy pathways in natural ecosystems. Pathways help to recycle scarce resources such as customer attention and customer-derived information'.

Early attempts to consider MIS have focused on the first two of these system dimensions: organisational capabilities and system functions. Wesseling and Meijerhof (2021) adopt a 'structural-functional' approach to their analysis of MIS and emphasise the strengths and weaknesses of system actors and functions (Wieczorek and Hekkert 2021; Elzinga et al. 2021). One critique of this approach – reflected in the literature on technology innovation systems - is that it fails to formally engage with temporality which is critical to defining the dynamic and changing role of the public and private sectors as missions mature. For example, the high degree of intended directionality in mission orientation shapes a more pronounced role for state actors in formulating these goals during the early stages of a mission and, consecutively, actively steering towards these goals (Schot and Steinmueller 2018) by implementing suitable measures and 'setting clear targets and milestones and the development of approaches to assess progress' (Wittmann et al. 2020: 74). Moreover, actors and actor constellations are often changing over time, increasing the complexity of governance as missions mature (Hekkert et al. 2020). In some studies of technological innovation systems, the changing nature and roles of actors are addressed by identifying time-bound 'episodes', an approach which we adopt in structuring our examination of MIS (van Alphen et al. 2009).

Thus, we take temporality seriously and propose a conceptual structure based on five sequential 'episodes' which may vary in length and complexity depending on the nature of the mission being considered:

- **Ideation** – which involves the formulation of possible mission objectives, timelines, and the nature of the mission challenge. This provides the basis for a discussion of objectives and approaches in the subsequent legitimation stage. Public sector actors are likely to be important in this episode in providing the evidence base on which mission ideation can be based. Private sector actors and citizens/end-users will be important in identifying the variety of technical solutions which might be available to address mission objectives and identify which of these options are acceptable to the general population.

- **Legitimation –** this episode finally leads to an agreement on mission objectives, timelines, scope, and stakeholder roles. The key activity here is discussion and consultation among stakeholders which is likely to be facilitated by public sector actors. Goals and roles may be strongly contested, but the coherence of stakeholder objectives is likely to be critical to mission success (Edquist 2004).

- **Implementation –** the working out of stakeholder roles and co-ordinated actions. This is the key functional and delivery stage of the mission and is likely to be the longest in terms of duration. Within the implementation stage, sub-stages may be distinguished during which the roles of different actors change or vary in importance. Public sector actors will here provide support for solution development, shape the regulatory climate and coordinate joint and collaborative action. Private sector actors will contribute entrepreneurial and innovative inputs and consider how their other activities can be aligned with mission objectives.
- **Completion -** missions may be timebound and success may be full or partial. Public sector roles here are likely to involve monitoring and evaluation of outcomes.

- **Retrospection** - consultation and the capture of learning from the mission. The role here is to provide feedback on improved MIS operations in future. Public sector roles would be to co-ordinate and convene. Private sector inputs will help to inform future actions.

Furthermore, we base our empirical approach on a conceptual model which not only identifies episodes in the development of a mission, but also extends the stakeholder groups suggested by Agarwal, Kim & Moeen (2021), i.e., public, and private sector actors to include citizens or end-users as well as key 'intermediaries' like community leaders and influencers in mission development and implementation (Figure 1.1). While the addition of citizens and end-users parallels that of the role of users in "user-innovation" (Von Hippel, 2009; Martiskainnen, Schot & Sovacool, 2021), we argue here that the role of citizens and end-users is more substantive and transformative. Indeed, we assume the role of the citizenry to be a lot more engaging and active in terms of openness and willingness to learn new social behaviours and norms and change old habits. Having said that, we do acknowledge that citizens, like other stakeholders, may not be a monolith and there might be apathy, or even active contestation about the right way forward even amongst the citizenry/ different end-user groups (for example, think of the substantial anti-vaccine sentiment which existed globally at the height of COVID). This makes it imperative for public-sector actors to identify the various types of citizen/ user stakeholders which may fall under at least four categories – champions/ advocates, interested, disinterested/ apathetic and actively resisting. Further, it is crucial for public sector actors to not only identify various contested parties and issues but actively engage in working towards the resolution of the same. Identifying and resolving "contestations" are another defining characteristic of MIS. This also reflects the idea that MIS addresses societal challenges that 'require technological, behavioural, and systemic changes' among the entire population (Foray et al. 2012; Mazzucato 2016) (as cited in Fittman, et al, 2021).

And, while government and other public-sector actors have a pivotal role to play in terms of helping resolve existing contestations, additionally we account for the role of what some scholars have identified as 'intermediaries' and community 'champions' (Stubbs, et al, 2022; Martiskainnen, et al, 2021). Given the wicked, contested and 'cross-disciplinary' nature of MIS, it is recognized that individual champions and/ or intermediary organizations help plug the gaps and cracks between the boundaries of traditional organizational stakeholders (both public and private) and help play the pivotal integrative role of harnessing knowledge spillovers, disseminating knowledge and role modelling change adoption. This is akin to the 'bridging' role of organizational sponsors and intermediaries like incubators and accelerators as identified in the entrepreneurial ecosystem literature (Amezcua, Grimes, Bradley & Wiklund, 2013; van Rijnsoever, 2022).

Figure 1.1: Episodes, key stakeholders, and roles within an MIS

Episode	**Activities/Outcomes**	**Roles of:**			
		Public Sector	Private sector	Citizens/end-users	Intermediaries/ Community Leaders/ Influencers
Ideation	Formulation of possible mission objectives, timelines, and nature of challenge, Provides basis for discussion of objectives and approaches	Synthesis of evidence base to define mission, surfacing of potential solutions and approaches. Harnessing of regional/ global knowledge spillovers.	Identify variety of solutions and technical options. Identify stakeholders and relevant networks.	Participate in needs analysis and ground-level articulation of the problem and associated pain points.	Provide leadership for user-innovation, i.e., prototyping, tinkering, experimentation and influencing public-private actors
Legitimation	Discussion and consultation among stakeholders. Agreement on mission objectives, timelines, scope, and stakeholder roles.	Convening role to support development of agreed objectives and approaches. Appreciation of contested issues and possible resolutions	Contribute to mission definition etc. Help identify supply/ value change conflicts and contestations	Willingness to engage in conversations about possible solutions for socio-behavioural change. Help build critical mass of adoption.	Serve as role models and advocates. Also help in mediation/ bridging of contested issues
Implementation	Working out of stakeholder roles and co-ordinated action. Progress towards mission objectives.	Provide – structure (including incentives), coordination (including knowledge coordination) and governance (including default nudges/ rules/ laws). Support for R&D/technical development. Develop appropriate regulatory/incentive structures. Co-ordination role, monitoring and measuring progress. Develop default nudges/ rules/ laws to facilitate ease of adoption. Also not just create rules and incentives but actively educate and mobilize users	Entrepreneurial/innovative contribution to mission objectives. Align indirectly related activities to/with mission objectives.	Openness to break-free from habitual/ inertial behaviour and learn new habits/ know-how associated with new emerging socio-technical solutions.	Knowledge dissemination and education, including translation of scientific-technological jargon into lay people language
Completion	Mission success – full or partial.	Monitoring and measurement of system level outcomes	Co-partners in monitoring progress and measurement of system level outcomes	Willingness to share ground-level data on progression, continued challenges and opportunities.	Mobilize and facilitate feedback collection and learning
Retrospection	Consultation and capture of learning from mission. Feedback into improved MIS operations	Evaluation, capturing lessons and feedback.		Sharing ground-level feedback on experiences with the solutions (what worked? what didn't)	Knowledge integration and dissemination

1.4 Studying MIS – our approach

This is a new area of research activity and unlike studies of regional or technology innovation systems, there is no agreed approach to studying MIS. Wesseling and Meijerhof (2021) suggest one approach, which builds directly on earlier thinking on innovation system functions and structure but considers the directional nature of mission-oriented innovation. They describe their approach as 'structural-functional' and comprising an initial 'structural' phase which provides context and structure and a second 'functional' stage in which engagement with system actors indicates the strength and weakness of system functions (Wieczorek and Hekkert 2012).

We draw on the staged approach suggested by Wesseling and Meijerhof (2021) but adopt an episode-actor approach during the second phase of fieldwork reflecting the framework included earlier in Figure 1.1.

1.4.1 Structural analysis

As developed by Wesseling and Meijerhof (2021) this comprises a problem-solution diagnosis phase and then a structural or institutional phase:

The problem-solution diagnosis involves scoping the societal problems and solutions implicit in the mission. This would define both the problem and potential technological solutions which are being considered and would consider questions such as:

- How do different societal problems and 'wants' relate to the mission?
- What technological and social solutions are relevant to the mission?
- How radically innovative are these solutions, and what is their state of technical (Technology-Readiness Level - TRL) and market readiness (MRL)?
- How would different stakeholders conceive the different episodes? What are their timelines?

Structural analysis focuses on identifying the main actors (in addition to private and public sector actors we recommend explicitly accounting for two more stakeholder groups – citizens/ end users and champions/ intermediaries) engaged in the mission and how the mission aligns with other related initiatives. Wesseling and Meijerhof (2021) suggest this involves questions such as:

- What actors are part of the mission arena and contribute to the direction and governance of the mission?
- What actors, networks, institutions, and materiality support the development and diffusion of the mission's solution?
- How does the mission arena align with existing formal and informal institutional structures related to the mission?

This element of the project (covering the problem-solution and structural analysis) would combine desk-based research with interviews with key policy and mission actors. This would help to define the set of organisations/firms to be interviewed in the second phase of the analysis.

1.4.2 Mission episodes and development

Considered in a more extensive set of interviews with system actors the aim here is to identify strengths and weaknesses within each element of the MIS and identify barriers to effective implementation and completion. For the case studies, we developed different topic guides for policy and business actors which aim to cover the ideation, legitimation, and implementation episodes. For policy actors, for example, interviews covered issues such as:

- What is the rationale for the specific mission and how was this decided upon? What other options were considered? How does this mission fit with other related (or inter-related) missions? (Ideation)

- Who do you see as the key stakeholders – who are you looking to collaborate with to achieve your goals in this area? (Ideation/Legitimation)

- To what extent have the mission targets/timelines been discussed and agreed with other stakeholders? What are the mission targets /timelines? Are these realistic and achievable? (Legitimation)

- What are the key policy measures (a) in place now and (b) being considered for the future? Have you looked at a range of policy options? (Implementation)

- What are the key challenges for policy in this area? Prompt around technology, demand and supply side issues – complexity of the issues, joined up policy making. (Implementation)

- What initiatives/ channels are in place to engage with the different stakeholders?

- What initiatives/ channels are being leveraged to coordinate knowledge sharing between various stakeholders (conferences, media – traditional and/ or social, FAQs on websites, etc.)?

1.5 Mission-study overview

We report three innovation mission-studies chosen to reflect different states of maturity. First, we examine the MIS related to domestic heat pumps. This is a well-developed technology, with an established mission innovation target, although implementation challenges remain significant. Second, we examine the mission relating to green hydrogen. Again, this mission has targets which are identified although perhaps less widely acknowledged and accepted than those relating to domestic heat pumps. Earlier in its development than the heat pump technology, this mission remains in its legitimation phase. Finally, we consider a potential mission around neodymium, one of the critical rare earths which provides the basis for many green technologies. This mission is at an earlier stage of development (ideation) with no clear established mission targets as yet.

In each case study our objective is to assess the robustness and validity of the episodes/actor framework outlined earlier rather than provide new insights into any of the areas of technology considered. For each of the missions, a document review was conducted and interviews were undertaken with key actors involved in the mission. Typically, a snowball sampling approach was used in identifying potential informants. Key individuals within Innovate UK, DBT, and DSIT provided the first contact list and further valuable contacts were then followed up.

The interviews aimed to identify strengths and weaknesses within each element of the MIS and identify barriers to effective implementation and completion. Where respondents agreed interviews were recorded and transcribed for subsequent analysis, and we report comments only in anonymised form.

The profile of interviews conducted were:

- ***For domestic heat pumps*** we conducted 12 semi-structured interviews with government officials (6) in England and Scotland, industry associations and federations (2), manufacturers and installers (3), and academic researchers engaged in more technical aspects of the development of heat pump technologies (2).

- ***For hydrogen*** we conducted 9 semi-structured interviews with government officials (2) in England and Scotland, industry associations and federations (2), private sector firms or consortia involved in hydrogen production, distribution, and/or production technologies (3), and researchers engaged in more technical aspects of the development of hydrogen technologies (2).

- ***For neodymium***, we interviewed 6 respondents, one from a UK government agency, two company staff, one private entrepreneur, one academic and one consultant.

Section 2: Domestic Heat Pumps

2.1 Introduction

Successive IPCC reports have documented the now essentially irrefutable evidence for human-induced climate change[1]. And, as the IPCC makes clear, while some global warming is now inevitable, appropriate measures are taken to limit further warming. As IPCC 2022[2] puts it 'unless there are immediate and deep greenhouse gas emission reductions across all sectors and regions, [limiting global warming to] 1.5ºC is beyond reach'.

According to the Grantham Research Institute on Climate Change (2022)[3] 'a step change in the pace of emission reductions is required for the UK to meet medium and long-term emission targets.' The UK government is committed to reducing the UK's CO_2 emissions. 'In 2019 the UK became the first major economy to pass into law a domestic requirement for net zero greenhouse gas emissions by 2050. Now, we are also committing to net zero greenhouse gas emissions by 2050 across UKEF's portfolio and operations'[4].

Defra (2022)[5] identifies a range of sources for CO_2 emissions in the UK. These include: energy supply, business, transport, public, residential, agricultural, industrial, land use and waste management. Within this, emissions associated with energy use in residential properties account for almost 20 per cent of the UK total. According to Defra (2022) 'In 2021, the residential sector emitted 68.1 $MtCO^2$, accounting for 19.9 per cent of all carbon dioxide emissions in the UK'.

Accordingly, whilst effective policy must necessarily include a programme of initiatives to reduce CO_2 emissions across the full range of sources, policies focused on reducing emissions from domestic settings are a necessary and important element of this overall policy programme. In this sense, reducing emissions from residential settings is just one mission within a much wider suite of related and ideally complementary missions. Promoting the use of domestic heat pumps forms part of this wider target of reducing emissions from home heating.

2.2 Domestic heat pumps – a 'solution driven' mission

Writers distinguish between problem and solution-based missions: 'missions being driven by a certain problem aim for a comprehensive understanding of the underlying problem and yet have to find a solution for the problem, solution-driven missions rely on an already identified solution for a specific problem' (Wittmann et al., 2021, p. 730). The domestic heat pump mission discussed here falls firmly into the category of 'solution-driven' missions, i.e., both the problem

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[1] https://www.ipcc.ch/reports/
[2] https://www.ipcc.ch/2022/
[3] https://www.lse.ac.uk/granthaminstitute/publication/climate-change-policy-in-the-united-kingdom/
[4] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1019141/UKEF_Climate_Change_Strategy_2021.pdf
[5] https://www.gov.uk/government/statistics/uks-carbon-footprint/carbon-footprint-for-the-uk-and-england-to-2019

to be addressed and the technological solution have already been decided. This has implications for the need for investment in discovery and science-based innovation (which would be greater in problem-based missions). Nonetheless, even solution-driven missions such as that relating to heat pumps, pose complex governance and implementation challenges (Wittmann et al., 2021).

The key point here is to recognise that the heat pumps mission is not concerned solely with technological innovation. Heat pumps are a mature technology; they have been widely adopted in several countries for some time. This is important to the UK mission because, from a policy development perspective, the mission is therefore fundamentally concerned with changing social values and norms of behaviour rather than accomplishing technological development. (This view is itself contested, however, as we discuss further below).

Certainly, the medium-term objective for policy must be to normalise the use of domestic heat pumps. Allied to this, there is a clear requirement that policy development involves measures that cut through the essentially unmanageable complexity of the issues involved. Nonetheless, the difficulty of the heat pumps mission is suggested by the comments by the Energy Saving Trust in its submission to the BEIS committee of inquiry into heat pumps:

> "*Past policy initiatives show that demand-led schemes (where consumers take up changes based on incentives), will not deliver the transformational change required to roll out low carbon heating to 29 million homes in less than 30 years*"[6].

The domestic heat pump mission in England is currently in the implementation episode. Within each episode of development of the mission we focus on the varying roles played by different actors – those in the public sector, private sector businesses, citizens/end-users, and intermediaries/community leaders/influencers.

While UK government departments set the overall policy direction on climate change for the UK, the governments and assemblies of the devolved administrations (Scotland, Wales and Northern Ireland) are responsible for climate change policy for their devolved areas[7]. In practice, this has led to distinctive approaches and policies. The quite different approaches to promoting domestic heat pumps adopted in England and by the Scottish government are a good example of this. In the short to medium term at least, the approach for England is predicated on incentivising heat pump adoption, while the Scottish government's approach is predicated on the early adoption of regulation. Here our primary focus is on the domestic heat pump mission in England although we include occasional reference to the devolved administrations.

[6] https://energysavingtrust.org.uk/report/consultation-response-to-beis-committee-inquiry-into-heat-pumps/
[7] https://www.theccc.org.uk/the-need-to-act/a-legal-duty-to-act/

2.3 Ideation

Throughout the UK, the promotion of domestic heat pumps is seen as just one of the measures necessary to meet commitments to reduce overall carbon emissions. According to BEIS,

> *'The Heat Pump Ready Programme forms part of BEIS' £1 billion net zero innovation portfolio, which aims to accelerate the commercialisation of innovative clean energy technologies and processes through the 2020s and 2030s. As a key solution for decarbonising homes, heat pumps will be critical for meeting the UK's legally binding commitment to achieve net zero by 2050'*[8].

This rationale also underpins policy in the devolved administrations. For example, according to the Scottish government, '*Heat pumps will be a strategically vital technology to deliver low carbon heat in buildings as part of the Scottish government's statutory target to meet net zero emissions by 2045*'[9]. There is also a recognition that 'the challenge of rapidly scaling up deployment is complex with impacts on a range of issues including fuel poverty, consumers, place, skills, supply chain, manufacturing, infrastructure and finance'[10].

While the contribution that domestic heat pumps can make to the achievement of net zero does provide a convincing, and largely evidence-based, rationale for intervention, there are potential problems with objective setting in this area. There is a clear risk that policy objectives are defined in terms of the social need, rather than in terms of what is realistic and achievable.

In the heat pumps case, the chronology of policy-making is such that it provides a context in which there are clear pressures to set targets defined by pre-existing commitments rather than based on consultation and an evidence-based assessment of what is realistically achievable. Certainly, heat pumps policy and the specific targets set for this policy post-date net zero commitments and the publication of related strategy documents. As one official put it, '*the 600,000 target that we must achieve by 2028 is really underpinned by a need to meet the carbon budgets that we have and is really the minimum number that we need to reach to achieve those carbon emissions targets'*.

Given the nature of MIS it is very likely that these risks will exist in the general case. And this is important because while there may well be a case for being ambitious in target setting, defining policy in terms of objectives that are likely to be unachievable, is always likely to be problematic.

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[8] https://www.gov.uk/government/publications/heat-pump-ready-programme/information-about-the-heat-pump-ready-programme
[9] https://www.gov.scot/groups/heat-pump-sector-deal-expert-advisory-group/#:~:text=Overview,net%20zero%20emissions%20by%202045.
[10] https://www.gov.scot/groups/heat-pump-sector-deal-expert-advisory-group/#:~:text=Overview,net%20zero%20emissions%20by%202045.

2.4 Legitimation

At the ideation stage of any mission, given the emphasis on finding the right scientific/ technological solution to a given problem, there might be a smaller set of stakeholders involved (Agarwal, et al, 2021). However, for the mission to be accepted as a socio-cultural "norm" requires the building of a much broader coalition (Edquist, 2004). Given the breadth of these challenges, both the UK government and the devolved admirations consulted with a range of key actors. As BEIS puts it '*Stakeholder engagement is a key component of the development of a future net zero Innovation*'[11]. Similarly, the Scottish government has established its Heat Pump Sector Deal Expert Advisory Group - a group of experts to provide recommendations to Scottish Ministers on the potential scope and content of a heat pump sector deal[12].

The need for alignment between stakeholders was recognised by multiple interviewees, while at the same time acknowledging the inherent challenges in doing so. The difficulties of this alignment are suggested by Figure 2.1 which was the result of a BEIS stakeholder consultation on heat pumps in 2021 and illustrates the diversity of views and opinions.

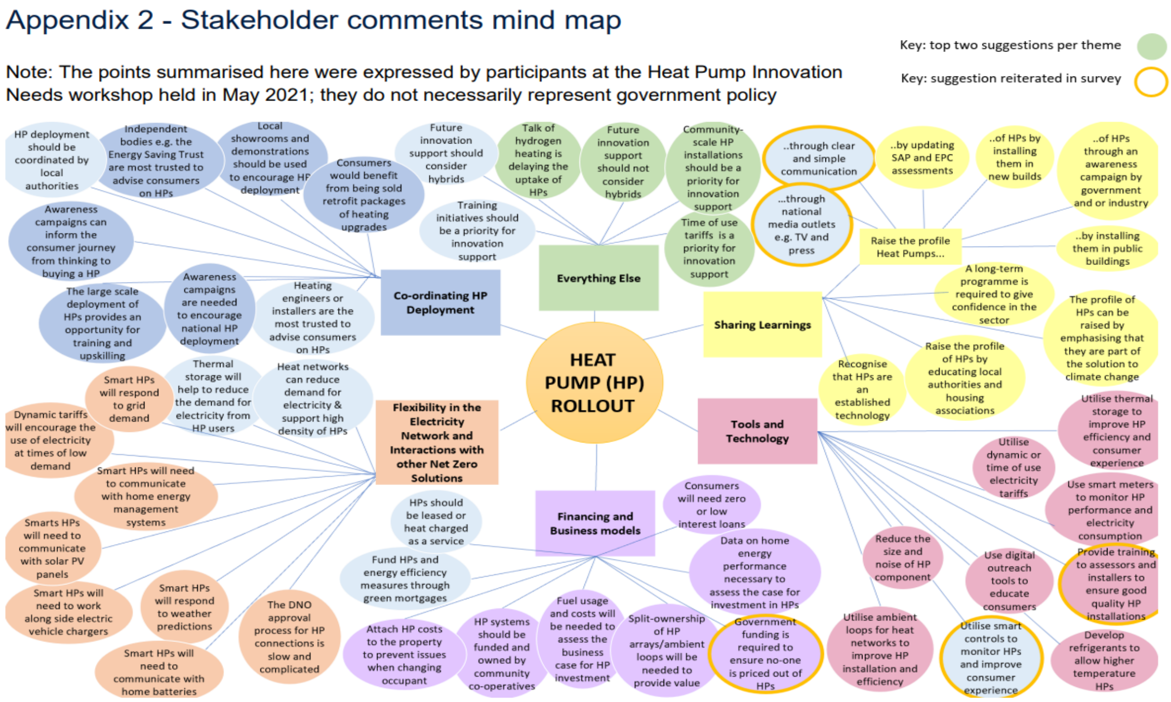

Figure 2.1: Stakeholder perspectives on the domestic heat pump mission

Source: BEIS (2021) Stakeholder engagement feedback Summary. Heat Pump Ready engagement summary (publishing.service.gov.uk)

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[11]https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1043235/heat-pump-ready-engagement-summary.pdf

[12] https://www.gov.scot/groups/heat-pump-sector-deal-expert-advisory-group/

Notwithstanding the challenges, many of our respondents also invoked past successes in the UK (examples shared were the 2007 ban on public smoking and the transition from coal dependence) as potential sources for lessons to be learnt for addressing the legitimation challenge of – *how can we "normalize" the usage of heat pumps and build a critical enough mass such that subsequently adoption is driven by word of mouth?*

Based on our interviews, it appears that there is some agreement amongst various stakeholders on key issues. All stakeholders acknowledge the risks of being "addicted" to fossil fuels and the need to wean UK consumers off oil and gas for their energy needs (it is important for us to point out here that there might be a selection bias in our respondent sample as all our respondents were actively engaged with heat pump adoption in some way or form). Both the war in Ukraine (and consequent rise in fuel prices) and the record summer temperatures in the UK may perhaps serve as tipping points for those who may still be unconvinced. Similarly, all stakeholders agreed on the key role of "installers" and the pivotal need to train, engage, incentivise, and leverage them as "experts" on whom consumers rely in terms of making decisions vis-à-vis heat pump installations.

However, there remain disagreements on multiple fronts which pose a challenge towards building a more robust alignment and a critical mass of adopters that will ensure that heat pump usage becomes a norm in the UK (as is the case in places like Finland – see Martiskainen, et al, 2021).

First, and fundamental to the mission, are disagreements around the potential for technological innovation and the potential for reduced implementation costs with domestic heat pumps. Some interviewees suggested that heat pumps themselves are an established technology and therefore the focus of innovation would relate to integrating heat pumps into domestic systems rather than on the improvements to the heat pumps themselves. However, there was little consensus on this. A typical view suggested the interface between the heating system and the heat pumps was where much of the innovation was required.

> *'it's most likely that some of the innovations are going to be the kind of stuff around heat pumps [for example, in the] integration of heat pumps with digital controls, initially kind of different zoning in your homes, linking them with sensors, understanding what really works in different areas, then you're going to have the kind of integration and innovation around the kind of wider smart home. Your heat pump might come on an hour earlier because it avoids the morning peak prices and [is more efficient for charging] your electric vehicle and managing other, significant, electricity loads in your house. In the wider system that is a huge area of innovation that still feels pretty nascent.',*

An example of this type of innovation related to the interface between a heat pump and other complementary technologies:

> '*Venta' has a great example of this. They do "net zero in a box" is how I would describe it. It's just a big black box, it goes outside your house, it has a heat pump, it has battery storage, so you can load shift your heat pump. It has mechanical*

ventilation systems in there for heat recovery, but also for air purification, and other bits and then does your hot water and stuff like that. And it means you can have one big thing that manages everything. You still have to do some retrofit around insulation and new ductwork and things like that. But those are the kinds of integrated solutions that offer real value'.

Other interviewees were more positive about the potential for innovation in heat pumps, although again views diverged falling into three main groups: the economies of scale position, the niche position, and the increased value position. The economies of scale position takes the view that the increase in demand will lead to the ability to improve mass production and this will reduce the price for heat pumps. One interviewee commented:

'One energy company says they can use that to get the cost down by half. They might be right, you know, people have done that, but then they've got no manufacturing track record, versus the Samsung's of this world who are big, heavy engineering firms. Now they might be right, and, you know, and absolutely should be supported to try and try and get there'.

Other interviewees were more sceptical about the technological frontier and the ability to drive down the production costs of heat pumps, reflecting the view that economies of scale had already been achieved in production elsewhere:

'It's worth saying that heat pumps are not a new technology, right? There are hundreds of thousands of buildings across Europe, not just homes, but commercial buildings and most commercial buildings will have some kind of heat pump, system, etc. So, there is a really open question about how much innovation [there is left to squeeze out] in terms of driving down that cost, etc. There is we have to be realistic about that'.

Secondly, there remain differences in view in terms of the role of grants as incentives for behavioural change amongst consumers. While many stakeholders see merit in grants as a first step, some wondered aloud whether scarce financial resources could be better used for subsidising subsequent operating costs associated with heat pump usage rather than subsidising just the capital/ installation costs. Respondents argued that consumers are less likely to install heat pumps despite grants for installation if they think that their monthly energy bills will go up with heat pumps in comparison to gas boilers. Furthermore, there were recommendations to take a more "whole house", systemic perspective and perhaps provide funding for changing the housing infrastructure (including insulation and heating pipes) rather than subsidising the installation of a heat pump in isolation. Additionally, there were suggestions for instead providing tax breaks (like in Finland) or low-interest loans (like student loans) as incentives.

Thirdly, our interviews reveal that there are multiple contested views on the efficacy of formal bans (of gas boilers) and coercive regulation. On one hand, many respondents argued that like past successes in the UK (smoking ban, seat belts, coal dependence, etc.) a ban on usage of gas boilers by leveraging the usage of the government’s coercive power would serve as a clear message. Respondents argued that a ban on gas boilers is also likely to have positive effects on manufacturers and installers who may be sitting on the fence vis-a-vis heat pump technology. However, at least one respondent wondered aloud about how coercive regulation might push people from a certain socio-economic background into fuel poverty. Also, multiple respondents argued that rather than going cold turkey, i.e., a complete ban on oil and gas, there might be merit in opting for hybrid systems (allowing for both gas boilers and heat pumps to be simultaneously available in the same house), which allows for gradual transitioning from a gas “addicted” populace to gas “weaned” populace. Indeed, a scholar who has studied heat pump adoption in Finland finds that the Finnish have been successful with a hybrid system. The risks of this hybrid, transitory strategy vis-à-vis climate emergency however need to be assessed more thoroughly.

Fourthly, stakeholders had conflicting views on the idea of district-wide/ communal heating networks[13]. While respondents saw merit in terms of economies of scale and reduction in waste vis-à-vis government’s idea of leveraging local/ regional heating networks, respondents also wondered if in a highly individualistic, heterogeneous, large country like the UK where people are culturally attuned to “own things” so that they can have individual/ private “control”, would a district-wide heating network find wide acceptance (despite success in Finland, albeit Finland is much more of a “homogenous” society and smaller country)? However, there was at least one respondent who pointed out that the UK has a history of local community action and there might be regions/ communities who may be more receptive to these ideas as well as certain structures would lend themselves more to heating networks than others (e.g., flats compared to detached houses).

Finally, stakeholders hold different assumptions about human/ consumer/ user behaviour. While some stakeholders assume that self-interest will drive the change in consumer habits and behaviours (and hence recommend leveraging incentives/ sanctions/ bans), others were more optimistic about consumers acting more pro-socially for the benefit of their communities and future generations.

As per structuration theory, for legitimation to successfully occur, it generally entails success in two earlier phases, namely – *signification* and *domination* (Giddens, 1984). While the signification phase is primarily focused on communicating the significance (or value or merit) of

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[13] Sometimes referred to as “central heating for cities”, district or communal heating networks are a system of insulated pipes which transport heat from a source (or multiple sources) to more than one end user. These are powered by centralised energy centres, which can be (but are not always) based on heat pumps. See: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/696273/HNIP_What_is_a_heat_network.pdf.

the new "norm" being proposed, the domination phase entails leveraging coercive power in the form of either incentives (or sanctions/ disincentives) or formal regulation to drive the desired appropriate behaviour. Legitimation has largely been achieved in terms of the importance of the ultimate objective – the de-carbonisation of domestic heating. However, as our interviews suggest achieving legitimation in terms of the role of heat pumps and their delivery at scale is still a work in progress: there's still a fair amount of progress that needs to be made with both communicating/ educating consumers (and other stakeholders) on the merits/ significance of heat pump technology (and what it means for the UK populace in the context of global climate emergency) as well as the willingness to leverage coercive power (albeit for the larger, public, social good) to help establish the domination of this technology (assuming there is enough scientific evidence that this is a more superior technology). Only once the government, as a primary owner/ champion/ stakeholder for this mission, can make some more progress on these fronts can we hope to truly establish the legitimation of heat pumps as the "norm".

2.5 Implementation

As the previous discussion suggests our interviews highlighted considerable divergence of view around the heat pumps mission. The current installation rate - about 30,000 units each year[14] - also emphasizes the challenge in achieving long-term targets. In this section, based on our interviews with mission participants, we explore the complexity of both the supply and demand sides of the equation. In both cases, we highlight challenges that came to light during our investigation and try to pinpoint areas where supporting innovation may increase heat pump adoption. Our findings suggest, consistent with the mission innovation literature, that no single intervention holds the key to reaching targets. Rather, policy needs to consider a range of factors from supply, to demand factors, to installation challenges, to integration opportunities, to financial incentive structures, and more. Parsing these themes by type of actor enables us to explore opportunities for innovation in each of these segments of the market and consider the relationship between actor incentives, observed barriers to implementation, and the interactions between them.

2.5.1 Private sector

Actors in the private sector have an important role to play in the implementation phase of mission-led policy. It is in this segment where targeted interventions may help increase innovation and entrepreneurship to support mission goals and where public coordination and leadership may be most effective in aligning activities and incentives with mission objectives. Unsurprisingly, many different types of private sector actors contribute to the MIS, from manufacture to installation.

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[14] https://institute.global/policy/three-birds-one-stone-how-greener-homes-can-solve-energy-trilemma

2.5.1.1 Heat pump manufacturers

In the previous section, we observed that opinions differed about the potential for heat pump manufacturers to make technological strides that would significantly improve their products and encourage uptake. Given that the reliability of supply was identified as a crucial bottleneck, finding ways to scale production could be a meaningful point of intervention. Projections suggest, and those we spoke with agree, that the heat pump industry is not currently producing enough units to meet mission targets. As one commentator reflected:

> '*We have to be honest about the supply chain. We do around 30,000 heat pumps a year, [but] we need to get to about 1,000 every five days. It's kind of several orders of magnitude, kind of challenge to overcome'.*
>
> *'Large multinationals are doing it [producing heat pumps]. We also have some domestic UK suppliers, [but] they're not able to manufacture in the quantities needed right now. I don't know why but it'd be interesting to understand what their barriers to scale are at the moment. But there is a reason that we have a four-month wait time'.*

The importance of the wait time in this scenario was re-emphasised by another respondent:

> *'I talked to people that want heat pumps, and they say the wait time is like three to four months at the moment to get a heat pump available and get it installed. And there's a problem with that because the realistic time you're going to replace your gas boiler with a heat pump is at the point that it fails. And if I have to wait four months to get a heat pump, well I'm not going to do that, am I? I mean, I want heating the next day, I want like 48 hours turnaround max for heat and hot water. So that's a problem. I think that is going to be one of the real challenges. If we don't make heat pumps available when people have the right moments to make that change, we'll miss the opportunity up to the point where the gas boiler ban comes in and all that problem goes away anyway unless we go down the hydrogen boiler ban and it then it becomes a problem with heat pumps again'.*

Innovators believe that with the right support, they can bring down the manufacturing costs, permanently, to £5,000, or perhaps even to parity with boilers in time (roughly £2,500).[15]

Interviewees also suggested that innovation to reduce the size of units, to minimize disruptions associated with installation (including facilitating integration with other home systems and reducing installation errors), and/or to bundle the unit with additional infrastructure (such as solar

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[15] https://institute.global/policy/three-birds-one-stone-how-greener-homes-can-solve-energy-trilemma

arrays), software and services (such as load shifting capabilities or heating as a service) could also bring consumer incentives closer in line with mission objectives. Significantly, improving integration and bundling/service packages require manufacturers to coordinate with other partners – whether these are retailers, energy companies, contractors, or installers – or innovate their business models to deliver these offerings.

2.5.1.2 Construction and related industries

While unit costs are certainly prohibitive for some, another significant cost relates to the broader refurbishments necessary to ensure that heat pumps work effectively. Upgrades to insulation, doors, windows, and other home systems are often required, which in addition to being costly and time-consuming, are also highly disruptive and difficult to adapt in much older housing stock. Coordination between trades is essential to minimize disruptions related to installation and to ensure the effectiveness of the unit once installed.

Even in new builds, a lack of attention to how units are handled by installers and how heat pump specs may require changes in home designs and construction phasing can cause delays, installation mistakes, and reduce unit efficiency:

> *'What we've discovered, once we've got all the supply chain in a room together is they don't talk to each other. So, the people who make windows, don't talk to the people who make frames. We don't talk to the people who make the walls. … if they all work together in a more collaborative way as a set of components that make up the building come together (which is the point of the Transforming Construction programme) you'll get a building that was built properly in the first place. And I think it's similar [with heat pumps] - you've developed a solution; it's not designed with the end installation in mind. This is definitely where Octopus Energy are going hard. They do think they can bring down the cost, both making heat pumps and installing them, and they're going to be installing them themselves.*

All of this suggests that heat pump installation and adoption might increase with greater dialogue between manufacturers, home designers, contractors and tradespeople involved in various stages of building, and others that contribute to the building as a *system* to develop unit design features (upstream) and adapt construction practices and develop appropriate skills to integrate them most effectively into homes (downstream).

2.5.1.3 Installers

Even if costly retrofits are not necessary, issues related to installation may also deter investment in heat pumps. Heat pumps are large and typically either take up more space indoors than a boiler or have components that must be housed in protected (yet accessible) locations outdoors. Furthermore, a boiler can be upgraded without any other changes to the heating system. Heat pumps are not a like-for-like change. What matters is how the heat pump as the heat generator interacts with other elements of the heating system. As an interviewee suggested:

> '*And second is the installation process. Because that's still a large part of it. They're not necessarily designed with installation in mind. They certainly don't design the product with installation in mind to combine with other things. And that's really where the bigger* opportunity *comes that it's not just a case of getting a heat pump on a house'.*

Installing heat pumps also requires heating engineers to use wider skills. These wider skills would involve considerations about the specific requirements of each building. As one interviewee suggested

> '*…we don't have enough good people. The success of condensing Combi gas boilers, because they're relatively easy to install, has created a big problem, because you've deskilled the generation of boiler fitters, who don't really think about the heat loss, heat load of a building in any sophisticated way. So, they just work on an* oversized *boiler, run it to higher temperature, it's inefficient, etc. But the consumer doesn't really care'.*

As this individual suggests, however, there are simply not enough people with the skills necessary to execute the number of installations required to meet mission targets. However, the issue is at once a problem of quantity and *quality*. This observation also demonstrates that these systems require a different mindset, and skillset, to install. Installing a heat pump is not the same as switching the boiler. It requires more training for those who are installing them. Due to the range of skills required at least one firm of heat pump installers has created a specialist group who are dedicated to installing heat pumps. It was reported to us that

> '*Energy Systems Catapult said one of the key things they learned is even for the [tradespeople] that were certified to work with heat pumps, they had to do a lot of post-installation scrutiny to make sure that things had been done appropriately. Because often the engineers were taking shortcuts or they were doing things in a way they thought was better, that wasn't necessarily better. Or they were making design choices that were inappropriate to the context of the installation. And as I said, that can lead to negative experiences. And so, there is a skills piece needed here to make sure that when all of these traders are out there doing these installations, it's giving people the outcomes they want, not just what might be thought about'.*

2.5.1.3 Financial sector

Retro-fitting the existing housing stock to make them suitable for the implementation of heat pumps is a costly task. It requires a great deal of resources. Where might those resources come from? The consumer is one source, but others might include private investors. The issue then becomes how can you attract private investors into the retrofitting of existing buildings. In the first instance, you might have portfolio owners of buildings and houses that might be able to introduce heat pumps. The example of social housing providers would be one example where it is possible to group housing. The Netherlands operates a programme where areas can group to gain a subsidy to introduce heat pumps, but this is mainly focused on public resources (OECD, 2022). The advantage of packaging housing is that you can gain economies of scope as a crew moves around an estate. Whilst that might work for social housing finance a difficulty is still to create a value mechanism for private investment.

To gain private funding for heat pump installation will require some method to package a group of properties to offer a scheme which households can opt into, rather like The Netherlands but with private money. An interviewee suggested one example in heat as a service:

> '*And so, one example of that is energy or heat as a service. It's how can I just charge you a flat fee for your heat and energy that meets your needs as a tenant or as a building occupier. But then the incentive is on me to lower the cost of that energy by improving building fabric, putting in heat pumps for the rest of it. And then the margin I make the profit I make is on the difference between what you pay me to deliver your service, which in theory should be better than what you're paying on a per unit basis'.*

This is an area where business model innovation is yet to develop. It was suggested that the challenge is that interventions on their own are not large enough for project finance.

2.5.1.4 Energy companies

The broader adoption of heat pumps will also be affected by the activities of and competition between energy companies. Gas companies, faced with competition from heat pump units that rely on electricity, have a strong incentive to champion alternatives. One interviewee noted that the current higher price of heat pump units enables gas companies to get first mover advantage in offering hydrogen boilers. If costs remain high:

> *'That would give the gas lobbies with their hydrogen boilers a really strong incentive to go, oh you can have this hydrogen boiler for cheap and we've got all these pipes already in the ground, it's just going to cost you X amount on your bill every month to turn those pipes to hydrogen'.*

In competing for customers, gas companies have a major advantage because they are well established, and the infrastructure is already there. This may have important consequences for perceptions of technological viability and political support for the heat pump mission:

> *'There is active competition between oil and gas interests, trying to push the hydrogen solution who've got really powerful lobbying arms really well connected, insanely profitable, huge shareholder interests in all of those versus electrification, which is largely made up of small heat pump manufacturers, and then energy networks that are regulated businesses and so can't lobby, like National Grid does lobby somewhat it from its private side, but as a regulated asset, it can't. And all of the decisions about network infrastructure [are] supposed to now be made independent of commercial interests. So, it's like two different worlds, you've got this world of like scattered voices, everyone kind of doing their own thing. Heat pumps are all kind of different. Not many levers, not many powers versus the massive incumbent commodity juggernauts who are like hydrogen is the future. And so that is the problem with this behavioural stuff […] is if we don't show people that they could have the same or better experience from heat pumps for the same price, or cheaper than it currently is, or than hydrogen will become in the future, then the de facto choice will just end up being hydrogen'.*

Some interviewees also questioned the capacity of electricity grids to handle the increased demand of large-scale shifts from gas to electric heating, even with efficient heat pumps:

> *'If you model a place where everyone's on gas, and everyone then switches to a heat pump and an electric vehicle, you're effectively tripling the size of the network that's needed there. It's a huge investment. And the way the regulated asset bases work, as I understand it, they struggled to make forward investment decisions, or they're not allowed to make forward investment decisions. They have to kind of invest based on what's needed, not on what's predicted. So that creates a bottleneck in terms of time. And then the other problem as well is from a kind of a larger property perspective or commercial perspective, if you need your substation to be upgraded to meet a large load. And I've run into this already with bus companies wanting to electrify their buses and saying we need a really big connection. It doesn't matter if the substation is already at like 98% capacity, if you tip them over the edge, you have to pay for 100% of the substation upgrades. So even if you only need like 2% of the additional capacity, you pay for all 100% of it. And then if someone else comes after you they get it for free, and that can be you know, I talked to one bus company, they were saying they were quoted like 25 million pounds to get like a megawatt of connection or something. They were like, we're obviously not able to afford that because we're a bus company'.*

While this case cites bus company electrification needs, similar problems could emerge for developers or councils seeking to implement large-scale transformations. As such, capacity challenges exist on the infrastructure side even, and perhaps especially, when demand is highly aligned with mission objectives.

Pressures on the electrical system could be mitigated by features such as load-shifting technologies or substation battery arrays. However, this respondent noted that there's only so much you can do with optimization. Eventually, you need to put more wires in the ground. Interventions that encourage and enable the expansion of the electricity grid to accommodate rapid and uneven growth in energy demand will play a critical role in the successful completion of this mission.

4.3.2 Intermediaries/community leaders/influencers

Intermediaries play a significant role in promoting the diffusion of clean technology (Aspeteg and Bergek 2020, Bergek 2020, Kivimaa, Bergek et al. 2020). Although intermediaries are not a homogenous group they may perform other roles in a variety of sectors. Examples of intermediaries include consultants and project developers and would include a convening role that Innovate UK played to improve the system (Bergek 2020). The roles of diffusion intermediaries include research and technology organisations that transfer knowledge, 'soft' intermediaries such as innovation centres, Chambers of Commerce that are more concerned with business model innovation, and systematic intermediaries who may organize and create the conditions to enable learning (Van Lente, Hekkert et al. 2003).

Within the interviews, the intermediary and influencer roles were raised through a discussion of trust, where personal experience led an interviewee to suggest the problem of how to resolve some of the issues of asymmetric information around expensive and disruptive work.

> *'Yeah, I've got some delivery discussions with a heat pump expert, a home heating expert of the week, one of the things they were talking about was no, are we going to go for another phase, again, going back to the National Federation of builders, where we're relying on largely white middle-aged men to turn up and do this work on your home? Are you going to trust them? You know, we all know about dodgy extensions, you know, bad things that have been done. You know, I came out of that meeting, thinking I want to set up a business that was entirely run with female installation engineers, Because, you know, they're more likely to be trusted. That is it seems really simple social science involved in some of this design thinking. There's lots of parties to say, you know, what's going to work? How who's going to be trusted? In this role? Energy companies generally aren't. So, who's the trusted provider? And all of this is it's a big question we haven't answered. And it's easy for governments to kind of ignore'.*

The trust issue may also relate to the widespread diffusion of knowledge in an appropriate form. A knowledge-in-use concerning heat pumps may need to diffuse through the target population before heat pumps are accepted as the default way to heat homes.

In addition, several interviewees discussed the convening role of Innovate UK. This convening role would be part of the 'diffusion intermediary' role, which would bring stakeholders together to consider the future ecosystem.

> *'And it's convening the people who understand the different aspects of the heat pump innovation system is where Innovate UK can add value. The work we need to be doing, particularly right now, when we have not a lot of funding, is to think much more about how we put the elements of a future ecosystem or a future market into place.'.*

Moreover, interviewees claimed that this convening role was hugely successful.

> *'And the biggest return stuff we've ever done has always been where we've got different parts of the system together, talk about what that future might look like, and how they will work together differently, and how their role would evolve in those future markets, future economies.*
>
> *…So that's where we tend to think the innovation opportunities probably lie in this space'.*

The role of intermediaries needs to be given more attention since they are critical to a well-functioning innovation ecosystem surrounding the heat pump mission.

2.5.2 Citizens/end-users

While much has been made of customer sensitivity to price, disruption, and time lags, mission-led innovation policy also requires that stakeholders explore mechanisms to get citizens/end-users to break free from habitual/ inertial behaviour and learn new habits/ know-how associated with new/ emerging socio-technical solutions.

Issues related to the costs of installation are reinforced by challenges in terms of the customer experience. One observer pulled no punches, noting that failing to ensure broad customer satisfaction at this stage of the adoption process could be fatal and retard broader adoption:

> '… *a challenge for the supply chain, for the sector, for innovators, for incumbents to come up with low carbon heating outcomes, which are better than what they have at the moment…otherwise, there's absolutely no chance. And if you get poorly installed heat pumps [resulting in bad experiences], you will get a massive consumer pushback'.*

This customer pushback can be seen in negative stories that have emerged in the media, which may be linked to poor installation. As early adopters, local authorities ran pilots within social housing, and these had run into difficulties because they were too early in the process and had not considered the installation and disruption that might be part of the installation. One interviewee commented:

> *'I ran into lots of examples where local authorities put heat pumps into social housing as kind of pilots in the kind of tens of units. The tenants had bad experiences. And then they had to tear them all back out again and put boilers back in. And so, I know several local authorities I work with won't touch heat pumps at all at the moment'.*

pumps relative to that with more traditional central heating and the challenges this raises in terms of consumer acceptability:

> '*The way we heat our homes now is far too hot, heat gradients across a room. But people are used to that. It feels different in a building that's run with a heat pump. You know, this idea of comfort is very different from sort of this social challenge in terms of acceptability'.*
>
> *'And then you also need the relationship with the people to it, you need to make sure that people are considered when you do these innovations. And so, you need to convene in some way to make sure that both the manufacturer and the optimizer and probably also to extend the network, think about the needs and behaviours of the person. And so, in the thing I explained to you a minute ago that end-to-end thing. That's why I'm making sure there's a behavioural element in that because you don't just design in my opinion, heat solutions for a property type. You also design it for an occupier type, you need to make sure that even in their extreme cases, they use it. A great example of this is electric vehicles and range anxiety. People's range anxiety doesn't come from their day-to-day use of their EV where they might do a few miles, their range anxiety comes from their exceptional journeys where they want to take all the kids and prams and the surfboards and the dog in the car to the beach on the other side of the country. That's what their range anxiety comes from. And so, in a heat context, it's about making sure that if their behaviour goes to that exceptional circumstance, and that might be I've got, I don't know, an illness and then once every so often that illness gets bad, and I get sick and I need my house to be warm for a long time. That's when we need to make sure that the heat pump design is capable of supporting that need'.*

'And so having things like not having warm radiators upsets people, they often like to dry laundry on there, it's a behavioural thing they often like to, I don't know, they like to rest against them on a cold day and things like that. So, it's quite a big change'.

Supporting this mission will require encouraging people to change how they relate to and the expectations that they have of the heating experience in their home. This may involve socializing advantages beyond cost savings, such as quality-of-life improvements:

'*... your home will be quieter. If you set it up properly, in terms of air tightness, and you've got proper ventilation, and heat recovery, you've got a building where the air quality is better inside it, you'll sleep better at night, you will be healthier, you'll be less affected by things like, respiratory disease, you'll feel brighter during the day'.*

2.5.3 Public sector actors and regulation

2.5.3.1 Building regulations

As noted above, heat pumps are relatively expensive to buy and install and, to be effective, often require additional investments in insulation, doors and windows, and sometimes electrical systems. In such a context, new builds present themselves as low-hanging fruit, where housing components can be selected to optimise heat pump efficiency, installation can occur before occupation and so eliminate disruption, and the higher cost of the unit can be rolled into the price on the promise that the homebuyer will recoup it on energy costs in the longer term. Policy has begun to shift to incentivise developers to choose heat pumps in new builds. However, it will take some time before they are fully in effect and for developers to seek to maximise, rather than just meet standards for, energy efficiency.

It has taken some time to gain some clarity in building standards and regulations concerning heat pumps or decarbonising buildings. A comment we heard from an interviewee suggested that it has been difficult for local authorities to enforce greater decarbonization of new housing through the planning system. The tale may be apocryphal but there appeared to be large differences between the developers and planners in their expectations of the improvements in energy efficiency that could take place in new-build housing. Two-thirds of local councils are aiming to be carbon neutral twenty years before the national target[16]. However, this can lead to conflict between the authority and developers. As an interviewee relayed:

'*[A] local authority lets land for a housing developer to build a new build site. New builds developer says we're going to do like a 2% improvement in energy efficiency versus the kind of UK average housing stock. The local authority says no, we're*

[16] https://www.local.gov.uk/publications/re-thinking-public-finances

> *not going to grant planning permission unless it's like a 90% energy reduction. The developer took them to the Minister for housing, and the Minister said, that because the local authority didn't have a local net zero strategy, they couldn't oblige the developer to do anything except the 2% increase. And so effectively, the local authority had its teeth removed altogether. That's the state we're in'.*

Announcements of changes to building regulations will require new homes to produce around 30% less CO_2 than current standards, and a 27% reduction in emissions from other new buildings from June 2022.[17] Currently, however, there is a context where some councils are requiring greater energy efficiency, and the building regulations are acting as a minimum standard. The minimum standard is set to increase. The 30% is an 'interim uplift' in energy efficiency expected in buildings. In December, the UK government formally announced plans to ban gas and "hydrogen-ready" boilers from new-build homes in England from 2025 (Ambrose, 2023a). This step-by-step approach is being augmented to provide a clearer road map for the future which might enable some market participants to go further along the road than is mandated by the present building regulations.

As in the 'British Columbia energy step code' some market participants are adapting more quickly. The code itself was assisted by market participants under a 'big tent' who spent time to develop the regulations and stakeholders together developing regulations to enable the necessary market adjustments. The key to its success was to transform the market which takes time (Glave and Wark, 2019).

Despite the positive direction of policy requirements and encouraging lessons from international experience, these initiatives will not, on their own, achieve mission thresholds. As one interviewee commented:

> '*If we just deal with new builds, we're never going to solve this heat problem…'*

New builds alone will account for fewer units than current heat pump installation targets. Projections by the Climate Change Committee suggest that if all new builds from now until 2025 were constructed with heat pumps, the UK could hit its increasing annual targets, but that after that retrofits will be required to make up the difference.[18] Consequently, the success of the bulk of this mission rests on the long-term retrofit market, which has its own set of challenges.

[17] https://www.homebuilding.co.uk/news/building-regulations-changes-new-homes-must-slash-emissions-by-30-from-2022

[18] https://www.theccc.org.uk/publication/sixth-carbon-budget/

Section 3: Clean hydrogen – from international agreement to national mission?

3.1 Introduction

Hydrogen is part of a suite of low-carbon solutions that will be critical for the UK's transition to net zero. As part of a decarbonised and renewable energy system, low-carbon hydrogen is a versatile replacement for high-carbon fuels used today – bringing down emissions across a variety of industrial sectors whilst providing seasonal energy storage, better energy security and flexible energy for power, heat and transport. Establishing a robust low-carbon hydrogen industry in the UK is a crucial element of the government's strategy to enhance economic recovery while fostering a more environmentally friendly energy framework. A transition towards hydrogen also has the potential to secure economic opportunities across the UK and position the UK at the forefront of the global hydrogen economy.

A key problem in decarbonisation is the timing mismatch between renewable electricity generation and electricity demand, which is solved through energy storage. In terms of the UK's decarbonisation objectives, hydrogen primarily serves as a store of energy and can be seen as an alternative to batteries or pumped hydro. It can be stored in several different ways such as salt caverns and disused oil and gas fields, and converted back to electricity when needed. Hydrogen can be transported in similar ways to natural gasses to end users, although most of the hydrogen currently produced in the UK is high carbon and used as inputs to industry.

Hydrogen is suited to use in a number of sectors where electrification is not feasible or is too costly, and other decarbonisation options are limited. For example, remote/untethered applications such as cargo ships or aeroplanes. It is also an input to many chemical processes and industrial production such as fuel for steam boilers and furnaces. Hydrogen has also been proposed as an alternative to boilers or electric heating options although policy is not currently pushing for domestic applications.

Low-carbon hydrogen is hydrogen that is made in a way that creates little to no greenhouse gas emissions. A colour coding system has been developed to distinguish the environmental impacts of different hydrogen production processes (see Figure 3.1). For example, green hydrogen – produced using renewable energy sources – is one of the leading forms of low-carbon hydrogen. Red/purple/pink hydrogen may also be a viable low-carbon alternative but because they rely on energy from nuclear power, have encountered political resistance in many jurisdictions. Blue hydrogen – produced using methane and carbon capture – is included in the UK strategies but is not carbon neutral.

Colour	Fuel	Process	Products
Brown/Black	Coal	Steam reforming or gasification	$H_2 + CO_2$ (released)
White	N/A	Naturally occurring	H_2
Grey	Natural Gas	Steam reforming	$H_2 + CO_2$ (released)
Blue	Natural Gas	Steam reforming	$H_2 + CO_2$ (% captured and stored)
Turquoise	Natural Gas	Pyrolysis	$H_2 + C$ (solid)
Red	Nuclear Power	Catalytic splitting	$H_2 + O_2$
Purple/Pink	Nuclear Power	Electrolysis	$H_2 + O_2$
Yellow	Solar Power	Electrolysis	$H_2 + O_2$
Green	Renewable Electricity	Electrolysis	$H_2 + O_2$

Figure 3.1: Colour code for hydrogen production (Sustainable NI 2023)

3.2 Clean hydrogen targets – production and costs

The UK is currently championing two different, though related, clean hydrogen missions. One focuses on production targets and the other on costs. While this report focuses on the latter, because cost reductions are so tightly tied to production scale, it is worth reflecting on production targets too.

In the British Energy Security Strategy (HM Government, 2022c), the government set a commitment to produce up to 10GW of low carbon hydrogen production capacity by 2030, with at least half of this from electrolytic hydrogen. This commitment represented a doubling of the 5GW ambition outlined in the 2020 Ten Point Plan for a Green Industrial Revolution (HM Government 2020) and the 2021 UK Hydrogen Strategy (HM Government, 2021).

One core problem for progress on hydrogen as a clean energy source is that it is currently three times more expensive to produce clean hydrogen than hydrogen produced directly from fossil fuels (Clean Hydrogen Mission 2021). Responding to this challenge, Mission Innovation has assembled a global coalition of countries to leverage innovation to reduce end-to-end hydrogen costs. Mission Innovation is a global initiative catalysing actions and investments in research, development and demonstration to make clean energy affordable, attractive and accessible for all. Launched at COP21 in Paris in 2015, it focuses on accelerating progress towards Paris Agreement goals and innovation-led pathways to net zero emissions. It is an international government forum that brings together 23-member countries (including the UK), the European Union, and one observer nation (Mexico) to pioneer clean energy innovation. In addition to Clean Hydrogen, the consortium has missions in zero-emission shipping, net zero industry, carbon dioxide removal, and others.

The Clean Hydrogen mission, to which the UK is a signatory, launched in 2021 and aims to increase the cost competitiveness of clean hydrogen by reducing end-to-end costs to 2 USD/kg by 2030. The Mission focuses on the following three areas to achieve the goal:

1. **Stimulating research, development and innovation**
   - Tackle the top research and development priorities with the greatest potential to drive cost reductions across the areas of production, distribution, storage, and end-use applications.

2. **Integration of production, storage, distribution and end use applications in hydrogen valleys**
   - Deliver 100 clean hydrogen valleys worldwide by 2030.

3. **Preparing the ground for the scale up of the hydrogen economy**
   - Preparing the ground for the scale-up of the hydrogen economy by building a coalition of partners to provide a clear and coherent enabling environment.

As mission participants, members are committed to developing and implementing their respective national hydrogen strategies aligned with the mission's focus to build a global clean hydrogen economy. They are also required to make individual commitments to fund and deliver innovation, research, and innovation into future sustainable, cheaper hydrogen production and infrastructure consistent with the mission's action plan. Each member country is required to contribute to the development of at least three hydrogen valleys. There are also expectations around supporting demonstration projects, accelerating market creation, creating opportunities for networking and knowledge exchange with an emphasis on engaging regulatory authorities, enabling the private sector to access information and collaboration opportunities, and providing representatives and in-kind contributions to the initiative.

3.3 Evaluating the mission to date

Like most MIS, the ecosystem around hydrogen cost reduction is complex. Broadly, cost reductions are considered possible throughout the hydrogen economy, from production, through distribution, storage and retail. These can be achieved through reductions in capital costs (e.g. production plant, storage infrastructure, distribution systems) which improve with scaling; process costs (e.g. production efficiency, transmission and conversion efficiency) which improve with learning through operations; and support costs (e.g. finance, insurance, options pricing) which improve as the hydrogen economy becomes more established and certainty within the market increases. The state of the UK hydrogen economy is still primarily focused on production at present and is therefore emphasising cost reduction through scaling and production efficiencies.

The domestic clean hydrogen mission in the UK is currently in the implementation stage. Within each episode of development of the mission we focus on the varying roles played by different actors – those in the public sector, private sector businesses, citizens/end-users, and intermediaries/community leaders/influencers.

3.4 Ideation

The Mission Innovation Clean Hydrogen Mission was launched in June 2021 to reduce the costs of clean hydrogen to the end user to USD 2/kilogram by 2030. It was expected that certain applications and locations would become competitive before others and achieved through both innovation and delivering at least 100 large-scale integrated hydrogen "valleys" worldwide. These would involve large-scale hydrogen production, infrastructure and end-use applications and pave the way for economies of scale and commercial viability, reducing cost and enabling market adoption (Clean Hydrogen Mission, 2021).

Since the launch of the mission, the UK has completed some of the commitments that are part of its participation in the Mission Innovation Clean Hydrogen Mission. In August 2021, the UK Government presented its national Hydrogen Strategy with a target of 5GW of low carbon production by 2030 (HM Government, 2021). This has since been updated to 10GW by 2030 (HM Government, 2022a). Concerning the mission goal, the strategy aims to use the production targets to "fully understand the costs around hydrogen, its safety where hydrogen is being used in new ways" (HM Government, 2021, p. 2). Cost reduction is anticipated toward the end of the targeted timeline with "significant cost reduction and commercialisation driving deployment across multiple markets" (HM Government, 2021, p. 27), to facilitate international hydrogen trading.

The strategy was preceded by the British Energy Security Strategy (2022) which offers nine points directly addressing lower hydrogen cost (HM Government, 2022c), although these are peripheral to the strategy's goals and do not form part of the related Energy plan objectives and key measures. These high-level strategies are supported by the Hydrogen Sector Development Action Plan (BEIS, 2022a) which sets out tangible actions in line with the strategic goals and considers cost at various stages of the hydrogen supply chain including production, storage and distribution, and end use, as well as the stakeholders which were informed by research on the UK hydrogen economy (BEIS, 2022c). In December 2023, the Department for Energy Security and Net Zero (DESNZ) published a Hydrogen Production Delivery Roadmap (DESNZ, 2023), which updates the delivery strategy through 2035 setting specific allocation goals via different award rounds. It also outlines a near-term ambition to have up to 1GW of electrolytic hydrogen and up to 1GW of carbon capture, usage, and storage (CCUS) enabled hydrogen in construction or operation by 2025 while also creating conditions for significant cost reduction. In summary, the cost target from the Clean Hydrogen Missions appears well embedded in the UK strategy although there is some disconnect between documents.

Those stakeholders we interviewed were aware of Mission Innovation and the clean hydrogen cost target, and some even participated in some of the organising meetings. However, none knew why that specific cost target was selected, what alternatives were considered, or who supported (or resisted) the cost threshold. In its joint communication, Mission Innovation stated that the 2USD/kg figure represented “the tipping point in unleashing the potential for clean energy to reduce global emissions, with clean hydrogen being cost competitive with other energy vectors in different industries across production, transportation, storage, and end-use” (Clean Hydrogen Mission 2021, p. 2). Significantly, there is no mention of what models were used to calculate this tipping point or how the target, described in USD, should be interpreted in other currencies over a nearly ten-year period.

Since the Mission Innovation initiative emerged from COP21, discussions are likely to have occurred at a high level of government, without much direct influence from the private sector, citizens/end-users, intermediaries, community leaders, or influencers. Capra and Motta’s (2023) account of the Italian experience with Mission Innovation appears to confirm this as they described Italy’s positions as influenced by and consistent with the Italian National Energy and Climate Plan (NECP) and participation in the European Strategic Energy Technology Plan (SET). Subsequent Mission Innovation meetings appear to have been attended by a wider group of stakeholders from each participating nation, but anecdotal accounts suggest that these focused on legitimating and debating implementation strategies for missions already agreed.

In this context, it is not surprising that the Mission Innovation target has not yet gained significant traction in the UK hydrogen landscape. Although cost reduction has been an important focus, the target has not been officially or explicitly embedded in any strategic or policy documents or in the communication of industry associations. Mission Innovation and the target were acknowledged in the Hydrogen Strategy Dec 2022 update to market (BEIS 2022a, p. 15) - which particularly highlights the UK’s involvement as one of the five co-leads of the Clean Hydrogen Mission in shaping the Mission’s Action Plan 2022-2024 that was published at CEM-MI Ministerial in Pittsburgh in September 2022. However, the mission has not (yet) been used to frame, promote, design, or implement a dedicated domestic hydrogen cost reduction strategy.

3.5 Legitimation

Evidence of coordinated engagement with mission legitimation is limited. This is due, in large part, to the fact that the hydrogen strategy is much broader than the cost reduction target and that the public sector is highly siloed. This has led to a lack of clear leadership on hydrogen cost reduction in which the public sector has played only an ad hoc convening role.

For its part, the private sector recognises that there is a mission but our discussions did not reveal a strong sense that it had played a role in defining the mission. To the extent to which cost is always a competitive concern to the private sector, some efforts have been made to identify supply and value chain conflicts and develop strategies to work towards lower end-to-end costs (usually involving an increasing scale of production). However, these were not catalysed or driven by the existence of the Clean Hydrogen Mission.

The constituency of end users is also quite broad, and fragmented, and hydrogen uses are sometimes competitive. As no end-user market is yet fully developed, there is still substantial uncertainty about which uses will be favoured and can sustain investments to increase production scale. As long as this is true, achieving critical mass in adoption will likely require engagement, coordination, and distribution across multiple markets. This means that end-user voices tend to be somewhat diluted in the legitimation process.

Intermediaries, such as industry organisations, tend to represent a membership that spans the hydrogen value chain and so have been hesitant to serve as advocates for specific solutions that cater to a niche within the value chain. This stakeholder in the MIS has so far preferred to focus on reducing barriers to scaling production and lobbying for support comparable to more mature green energy infrastructure than structure, debate, or champion any particular mission.

It is worth reflecting on the question of fragmentation and leadership, as this is an important reason that the mission has not catalysed the policy community and supportive incentive structures. The UK hydrogen economy comprises a variety of government departments and institutions, industry and their trade associations across the four UK nations, as well as investors, research organisations and end users of hydrogen. Of these, the demand side of the economy (end users) appears to be least discussed in the strategies, action plans and supply chain research, perhaps because the UK Hydrogen Economy 2020s Roadmap (HM Government, 2021, p. 29) assumes consumer acceptance to be secured across end-use sectors toward the end of the decade (2028-2030).

Despite the lack of consensus on specific mission objectives, the UK hydrogen economy is strongly networked with numerous institutional linkages between stakeholder types (Figure 3.2). Key connectivity efforts include:

- In July 2022 the government appointed a hydrogen champion to bring industry and government together (HM Government, 2022b). The appointed champion is the Chief Executive of a FTSE250 clean energy firm and is co-chair of the Hydrogen Delivery Council (formerly Hydrogen Advisory Council) which guides the delivery of the Hydrogen Strategy (2021), the British Energy Security Strategy (2022c) and the Powering Up Britain Energy Security and Net Zero Plans (2023).

- A Hydrogen Investor Roadmap (HM Government, 2022d) was published to 'support investor engagement' (BEIS, 2022a, p. 6), alongside the BEIS (2022b) infographic of the hydrogen funding landscape.

Notably, however, research organisations do not appear to be institutionally linked despite mentions of research and development as a key theme for metric monitoring (BEIS, 2022a, p. 39). Although supporting activities for Research and Innovation are considered in the UK Hydrogen strategy (HM Government, 2021, p.26), research is not included as a key area within the report and is not included in the summarising diagram of the Theory of Change for sector development (BEIS, 2022a, p. 38).

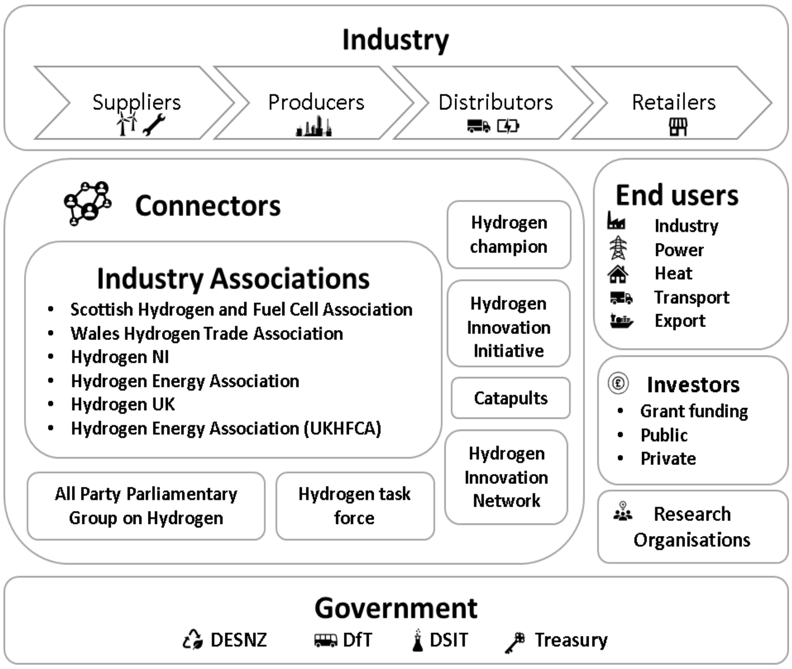

Figure 3.2: Stakeholder map of the UK Hydrogen Economy

Source: Authors.

3.5 Implementation

Our interviews indicated that while the mission goal of reducing cost is considered very important by all stakeholders, it is not the primary focus for any - rather it is variously seen as either an outcome of achieving scaled production (supply side view) or as an intermediate step that will enable mass uptake of production (demand side view). As a result, while progress has been made towards hydrogen objectives, the mission does not appear to have been decisive in driving it.

3.5.1 Private sector

Missions are devised, in part, to incentivise the private sector to generate innovative solutions in alignment with mission objectives. As stated above, the objective of cost reduction is relatively uncontroversial and largely in the interests of businesses along the value chain anyway. Consequently, while progress is being made, and private sector innovation is playing a role, it is difficult to say that the existence of the mission has caused businesses to prioritise, accelerate, or improve cost-reducing innovation performance (or, indeed, to pass cost savings on to customers).

The UK hydrogen economy is nascent with numerous firms, while aware of government ambitions to scale and the opportunities that may avail, still conducting small-scale projects:

> *"A lot of the government strategy for hydrogen is massive industrial, top - down, how do we change industry. … But we're not that - we're bottom - up, dealing with an issue - let's start small and see where it goes".*

Cost remains too uncertain to be a tangible target at present:

> *"The technology is not mature enough - nothing works the way we think it's going to".*

Nonetheless, organisations in the private sector have a large role to play in the implementation of the mission. Not only is industry expected to deliver cost reductions through scaling production, but also through technology improvements throughout the hydrogen supply chain. Both production and R&D require significant capital investment which interviewees highlighted remains a challenge.

Although the government has recognised the importance of ensuring private investor participation in the hydrogen economy (HM Government, 2022d), respondents indicated that there remains significant uncertainty in terms of future policy which may significantly impact demand. Respondents suggested that this uncertainty strongly affects the willingness of investors to fund capital-intensive production facilities, or invest in R&D.

> *"If you're an investor, you want to know that there's going to be a market. The government could kill the market through regulation, or it could put a huge subsidy behind production which means that there's a massive high-margin market in the near term."*

Until the private sector is willing to invest, the focus remains on reducing uncertainty through implementation and:

> *"getting kit on the ground and getting government support to get kit on the ground".*

The importance of looking beyond the private sector was reiterated by several interviewees, based on the recognition that hydrogen is attempting to address a problem not currently addressed through the free market alone:

> "*there's only so much industry can do*".

> *"it needs to be subsidised enough to make sure that it's cheaper than what they would do carrying on using hydrocarbons".*

Therefore, intermediaries and government still have a strong role to play if they want the private sector to drive down costs through scaling and technology improvements.

3.5.2 Intermediaries

Intermediaries play an important role in helping the private sector navigate developments in the industry. They can also be important conduits, transmitting information to the public sector about challenges and bottlenecks in mission implementation. These intermediaries are established by both industry and government. For example, the industry has established the UK Hydrogen Fuel Cell Association which has a membership of over 100 firms across hydrogen production, distribution, storage and supporting services and components. Government has established the Hydrogen Advisory Council which brings together diverse industry representatives, financiers, several government departments as well as representatives of the devolved nations.

Interviews indicated that intermediaries such as industry associations do not focus on the cost reduction mission because that is *"too technical for associations - the focus is rather on helping members grow"*. This is partly because associations tend to represent members across the supply chain and a wide variety of sectors and are reluctant to develop policies or initiatives that risk disadvantaging or prioritising, any one segment.

Similarly, the recently appointed Hydrogen Champion, representing industry and bringing their requirements into government planning, has recently released a report (Toogood, 2023) which is strongly aligned with the UK Hydrogen Strategy and does not directly address costs.

The landscape of UK hydrogen intermediaries is still developing rapidly. During the period of this research, hydrogen associations have rebranded and interviewees suggested that there is a need for consolidation. The number and diversity of hydrogen associations, advocates, champions and conferences reflect not only the diversity of views about the direction the industry should take, but the nascent stage at which the industry finds itself:

> *"The world of hydrogen is about press releases rather than spades in the ground".*

> *""There are too many voices - a lot of different groups all lobbying".*

Although there appears to be scope for consolidation within the UK hydrogen economy, interviewees highlighted that there is also room to expand connections with sectors that are more developed:

> *"The space is a little insular, dominated by gas incumbents. Maybe there is value from other sector stakeholders to learn from their approaches and experience."*

3.5.3 Citizens/end users

The cost mission was considered by interviewees to be particularly appealing for end users - there is such a diverse range of end users, from industrial processes to home heating, which cost provides a "*nice metric to focus on*".

In terms of the UK Hydrogen Economy 2020s Roadmap (HM Government, 2021, p. 29), end users are not yet fully engaged, and the interviews highlighted the disconnect with the demand side of the hydrogen economy.

> "*Consumer acceptance and preference, as well as the safety case, are still uncertain*."

Interviewees noted a chicken-and-egg problem that inhibits the incorporation of the cost mission. Since there are a wide range of use cases for hydrogen from shipping to household heating, each with their own distribution and storage mechanisms and related cost profiles that link hydrogen production with end use, policy efforts that look beyond production require consideration of end use, but this is only considered at later stages in the Roadmap. It is therefore difficult for policy to focus on more than production at this time. As a result, the mission is difficult to incorporate into policy until the strategy on end use is articulated in more depth.

Recent citizen opposition to hydrogen projects suggests that a strategy for securing widespread acceptance of domestic uses is needed. During our research, a planned pilot "hydrogen village" scheme, which would trial replacing home gas supplies with hydrogen, was cancelled due to local opposition (Ambrose, 2023).

3.5.4 Public sector actors

The public sector is driven primarily by the UK Hydrogen strategy, which has limited engagement with the cost mission. Interviewees suggested that an important role for government at present is not to drive cost, but rather to 'de-risk' commitments in various ways including developing an options market, guaranteeing (offtake) demand and offering subsidies to level the playing field with alternative energy options. Interviewees highlighted the disparate approaches that government departments have taken to implementing the UK Hydrogen Strategy and that there is a need for greater unified systems thinking - precisely the purpose of a policy instrument such as the Hydrogen mission. For example, an interviewee highlighted that a home heating pilot project was funded and implemented to start producing and distributing hydrogen by late 2023, but the department responsible for the decision to enable end users to heat their homes was unlikely to be ready in 2023. This project was later cancelled due to local opposition and supply uncertainty.

The mission itself was acknowledged by public sector interviewees but, since it is not discussed within the UK Hydrogen Strategy, it did not feature significantly in their planning, decision-making for investments, grants and subsidies, and upcoming decisions on regulation changes intended to create an interim market through blending hydrogen into the gas network system. Although various government departments have disparate plans for implementing the UK Hydrogen Strategy, it does appear that implementation of the strategy is comprehensive, considering capital expenditure support, R&D investment support, and numerous initiatives to build coordination between stakeholders into the development of the hydrogen economy.

A main takeaway in reviewing public sector actors and their implementation of the Hydrogen mission is that, given the importance of the UK Hydrogen Strategy in driving public policy and planning, any future missions need to ensure they are discussed and incorporated within these key government documents.

Section 4: Neodymium - from challenge to future mission?

4.1 Introduction

Neodymium (Nd) is one of the most important rare earth elements (REEs)[19] that are, together with iron (Fe) and boron (B), used to make the permanent neodymium-iron-boron (NdFeB) magnets that go into electric vehicles (EVs), wind turbines, medical imaging machines, computers, mobile phones, drones, tanks and other defence, health and consumer equipment. In its 2023 criticality assessment of 87 non-energy raw materials based on their economic importance (value added to diverse EU manufacturers) and supply risks (global supply concentration, EU sourcing, governance index etc), the European Union (EU) placed neodymium (a 'light' REE) among the group of 34 critical raw materials (CRMs) (EU 2023). Similarly, based on its importance to energy (demand and substitutability) and supply risk (basic availability, producer diversity, competing technology demand, political/regulatory/social factors etc), the US Department of Energy's 2023 Critical Materials Assessment report reviewed 38 materials, out of which neodymium emerges among the seven materials classified as critical in both the short (2020-2025) and medium (2025-2035) terms (see Figures 4.1 and 4.2).

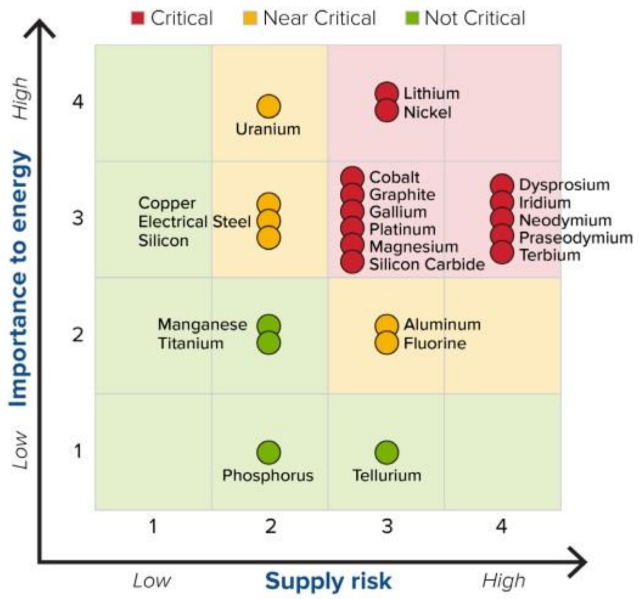

Figure 4.1: Short-term (2020–2025) criticality matrix

Source: US Dept. of Energy, 2023.

[19] The rare earth elements (REEs) consist of the lanthanide elements plus scandium and yttrium, which have similar physical properties and are often found in the same ores/deposits. Specifically, REEs include the light REEs (LREEs) such as lanthanum, cerium, praseodymium, **neodymium**, samarium, europium, and the heavy REEs (HREEs) gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium, and yttrium (MIT, 2016).

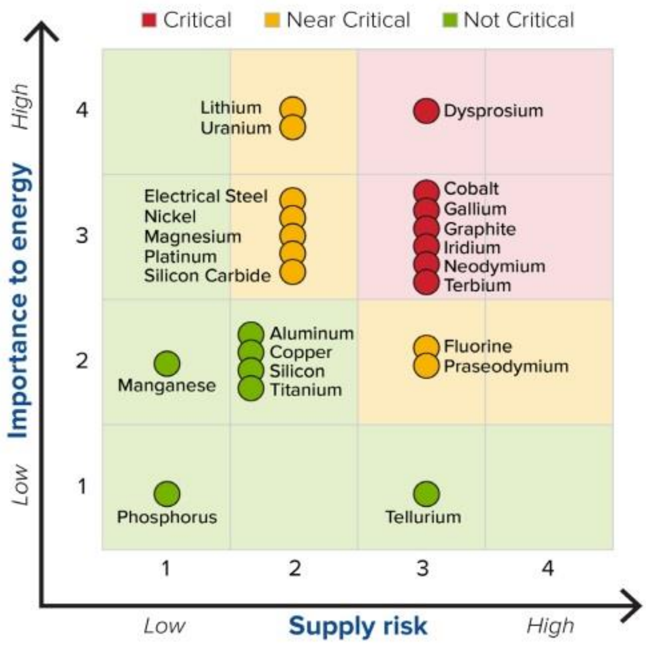

Figure 4.2: Medium-term (2025–2035) criticality matrix

Source: US Dept. of Energy, 2023.

A major factor in the assessment of neodymium as a critical element in both Europe and the USA pertains not only to its wide-ranging applications but also the dominance of a single player (China) in the global market for, not just neodymium, but also all the REEs. In fact, Europe and the rest of the world depend on China for the supply of up to 100% (of heavy REEs) and 85% (of neodymium and other light REEs) (see Figure 4.3 and EU, 2023).

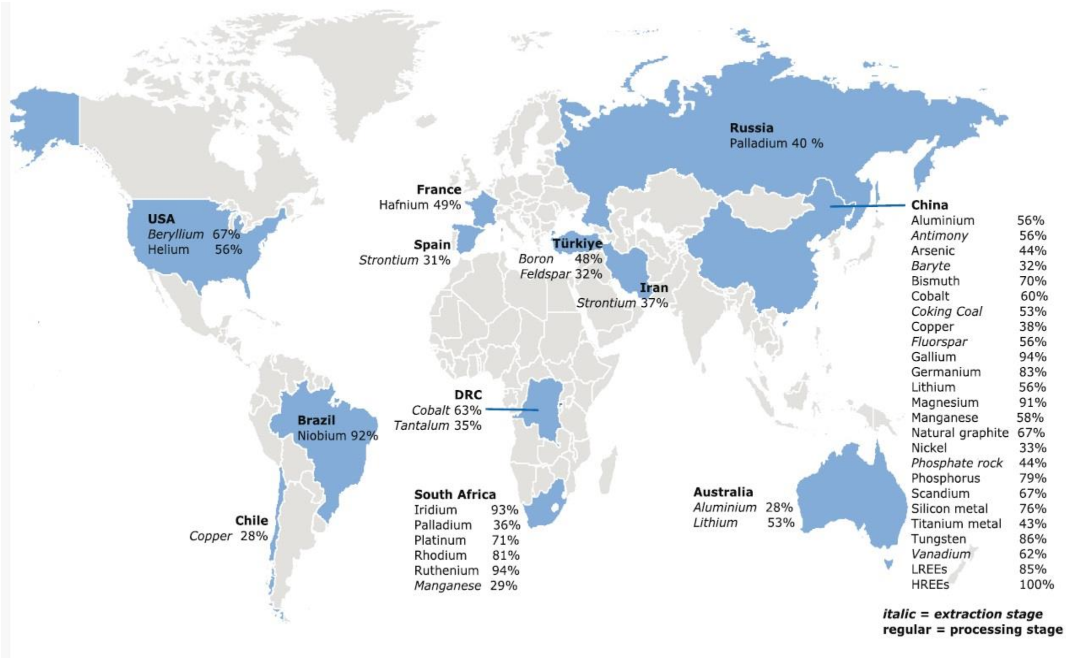

Figure 4.3: World map of the main global producers of the raw materials listed as Critical (CRMs) for the EU in 2023.

Source: European Union, 2023.

Chinese dominance in the permanent magnet value chains increasingly spans over the upstream and downstream stages (mining, refining and manufacturing) of magnet production (see Figure 4.4). However, these metals "are important strategically for the UK" (Powell-Turner and Antill, 2017).

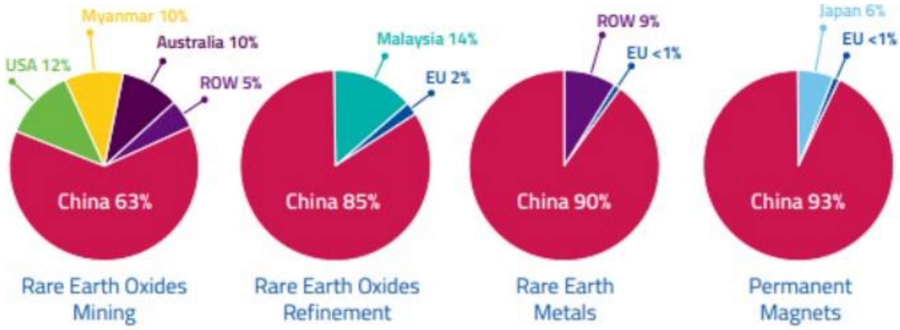

Figure 4.4: Chinese dominance over the rare earth permanent magnets value chain

Source: European Commission, 2022.

For Britain, and indeed other European countries, the stakes are high because magnets made mainly from neodymium have critical roles to play in the transition to net-zero strategy and green economy generally. Neodymium finds applications in both the so-called 'mature' (glass industry, catalysts, lighting, and metallurgy (except battery alloys)) and the high growth 'developing' (battery alloys, ceramics, magnets, defence and aerospace) market sectors of industrial economies (Goonan, 2011). Figure 4.5 provides an overview of neodymium use.

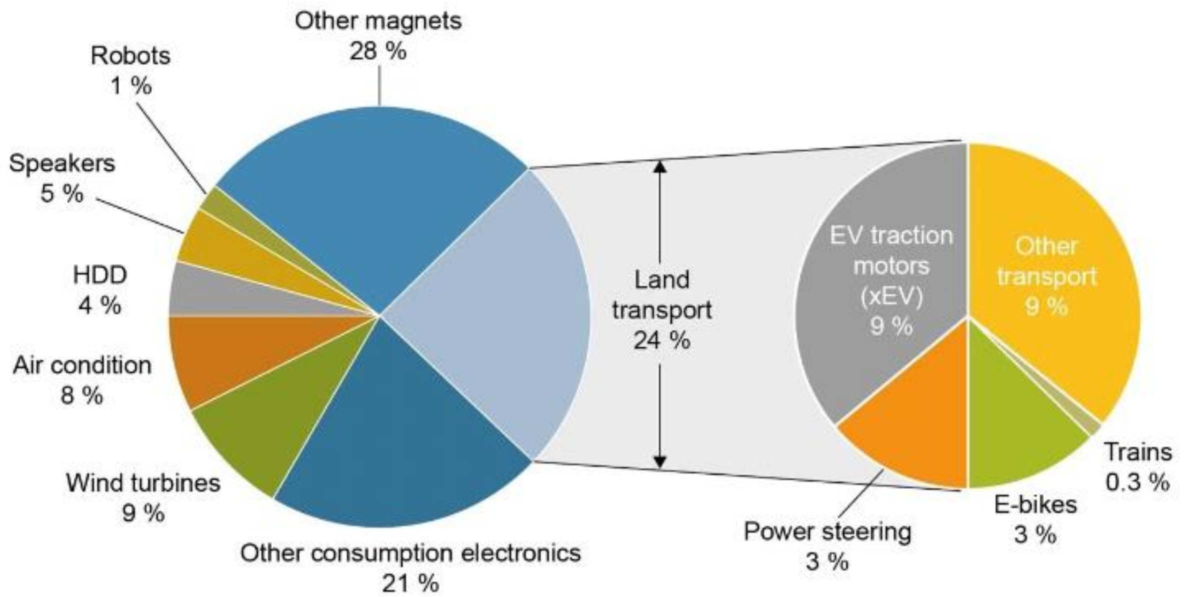

Figure 4.5: Global use of neodymium iron drill magnets in 2019

Source: Figure 3-3 in http://mima.geus.dk/wp-content/uploads/MiMa-Rapport_2022_01_Online.pdf.

4.2 International and UK policy context

The importance of neodymium (and indeed other REEs) has prompted recent efforts towards ensuring the diversity, resilience and sustainability of global supply chains (see figure 4.6). On 16 March 2023, the EU unveiled a proposal for its Critical Raw Materials Act (CRMA) for which the bloc secured a provisional agreement in November 2023. The proposed act aims to: (i) increase and diversify the EU's critical raw materials supply, (ii) strengthen circularity, including recycling, and (iii) support research and innovation on resource efficiency and the development of substitutes. The overarching goal is to strengthen the autonomy of the EU in the supply of key raw materials used in EVs, solar panels, batteries, wind turbines and digital technology (European Commission, 2023). This was informed by the recognition that "EU is vulnerable to supply risks because these raw materials are sourced from a limited number of countries." (Clifford Chance, 2023). Thus, the act sets out to, by 2030, ensure that EU's extraction, processing, recycling and external sourcing of CRMs are at least 10%, 40%, 25% and 65% of the bloc's total annual consumption, respectively[20]. Similarly, the Mineral Security Partnership (MSP) signed by the US, EU and ten other countries "aims to accelerate the development of diverse and sustainable critical energy minerals supply chains"[21]. Other efforts towards

[20] https://www.consilium.europa.eu/en/infographics/critical-raw-materials/
[21] https://www.state.gov/minerals-security-partnership/

addressing supply risks associated with minerals considered critical to the digital and green transitions include the EU batteries directive (now regulation), the US-UK Atlantic Declaration, the Green Deal Industrial Plan and the US Inflation Reduction Act. However, efforts like these are largely regional (EU-wide) or bi/multi-lateral agreements the UK enters with other countries (see Figure 4.6)

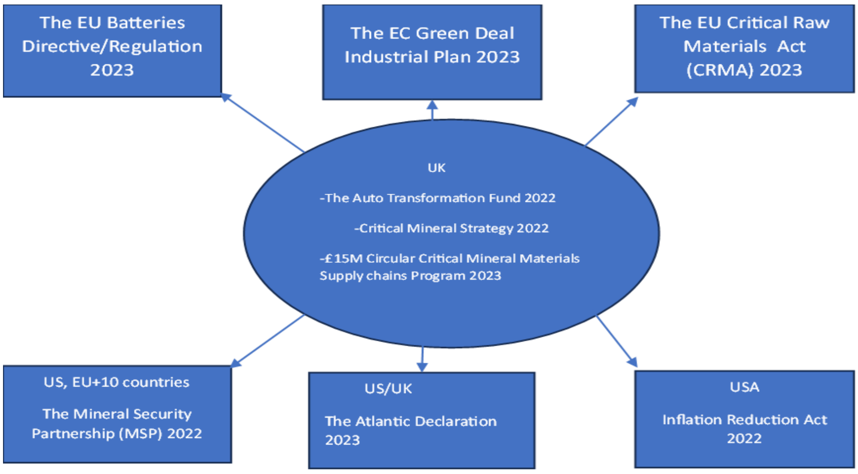

Figure 4.6: Regional, bilateral and national UK policies/efforts on securing REEs supply chains/clean energy transition

Source: Authors.

In July 2022 the first UK Critical Minerals Strategy (CMS) 'Resilience for the future' was published "to mitigate risks and to improve the resilience of critical mineral supply chains" (BEIS,2022). The CMS included the following objectives[22]:

> *'A resilient supply chain of critical minerals will support manufacturing of clean technologies in the UK – including zero-emission vehicles. This will ensure the UK maximises the benefits from the transition to net zero and supports tens of thousands of high-quality green jobs across the UK'.*

The 2022 Critical Minerals Strategy focused on three themes – accelerating the development of the UK's capacity to produce and recycle critical minerals, and to collaborate with international partners and suppliers to ensure continuity of supply. It notes UK strengths in R&D and responsible finance but notes continuing challenges with 'increasing recovery, reuse and recycling rates and resource efficiency, to alleviate pressure on primary supply'. An update on the Strategy (March 2023) cites several developments[23]:

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[22] See https://www.gov.uk/government/publications/uk-critical-mineral-strategy.
[23] See https://www.gov.uk/government/publications/uk-critical-mineral-strategy/critical-minerals-refresh-delivering-resilience-in-a-changing-global-environment-published-13-march-2023.

- The launch of an independent Task & Finish Group on Critical Minerals Resilience for UK Industry to investigate the critical mineral dependencies and vulnerabilities which reported in December 2023[24].

- Collaboration on critical minerals with international partners and engagement through the Minerals Security Partnership, International Energy Agency and G7.

- UKRI's Circular Critical Materials Supply Chains (CLIMATES) fund was launched with an initial £15m budget to focus on making the UK's Rare Earth Element supply chains more resilient and boost the circular economy. The CLIMATES fund aims to "support the development of innovation in primary (mine to magnet) and secondary (End of Life to magnet) supply chains…[through] … international collaboration, skills development, investment (public and private), policy advice and standards development"[25].

- A £65.5 million Accelerate-to-Demonstrate (A2D) Facility, under the Clean Energy Innovation Facility (CEIF) platform includes a dedicated funding pillar on technology innovations for critical minerals in developing countries.

Another significant development in July 2022, was the establishment of a £145milion rare earth magnet alloy maker at East Yorkshire, Pensana Plc.

Although the CMS, the CLIMATES program and related investments remain the best approximations of any UK attempts at public policy for NdFeB magnets, there is still no clearly formulated set of national targets/objectives or innovation missions relating to neodymium. This was confirmed by one of the CLIMATES team members in an interview (Interview 2) and sets the context for our discussion of ideation and legitimation.

4.3 Ideation

Here we explored, through semi-structured interviews with our respondents, the ideas behind the existence or possibility of a potential mission on neodymium magnets and the objectives, timelines, and challenges for such a mission. This is intended to provide a sound basis for informed policy formulation based on feasible objectives and approaches.

One of our respondents confirmed that the "*UK neodymium magnet supply chains are almost non-existent*". They added that although Less Common Metals Plc (LCM) produces magnet alloys here in the UK and that the government has made a significant investment in the East Yorkshire company, Pensana Plc, "*most neodymium metal magnets are coming into the UK in manufactured [forms]*". Corroborating this, another respondent added:

> "*You probably know that about 90% of [neodymium] permanent magnets come from China and there isn't at the moment a UK supply chain. [However] some*

[24] See See https://www.gov.uk/government/publications/task-and-finish-group-industry-resilience-for-critical-minerals.

[25] See https://iuk.ktn-uk.org/programme/circular-critical-materials-supply-chains/.

> *organizations are developing that [including] looking at the secondary [recycling] supply chains*. *So, Ionic Technologies Plc, who are at Belfast are looking at taking spent magnets and chemically recycling them, and there is an organization in Birmingham called HyProMag [who are also looking at recycling used magnets]*"

Our interviewees highlighted the CMS and CLIMATES funding as significant recent policy developments noting the objective of the CLIMATES program led by Innovate UK to:

> "develop work on rare earths… across the country and…*support innovations in the recycling of rare earth elements, as well as research and development, engagement with international partners and activities to identify and support future skills needs*."

However, as observed by a respondent,

> "*outside the Critical Mineral Strategy, which doesn't highlight specific targets or specific levels of production domestically within the UK, there's no such [mission targets, objectives or timelines on neodymium magnets]*".

But is an innovation mission on neodymium feasible? If so, what are the major challenges to such a mission?

All six respondents agreed that an innovation mission on neodymium magnets in the UK is important to secure the supply of the critical mineral that is critical for the UK digital and green technology transitions. However, it was observed that such a mission target is going to be "*difficult in the neodymium sector…given the kind of numerous minerals that are needed to produce a magnet*". Another raised the problem of the lack of both sufficient ore deposits in commercial quantities and the domestic market in the UK to permit the creation of a viable neodymium magnet supply chain.

Other respondents suggested that since "*currently there's no domestic magnet production at scale [that is] required to support the three million electric [vehicles] drive units which should be produced in the UK by 2030*", a neodymium mission targeting the domestic sourcing of some proportion of the magnets for these drives can be set within the time frame. Another respondent argued that since "*the UK does not have the ore deposits—they're in our computers and electric vehicles and central heating pumps and power tools and all the places where you see…and so the idea that we can get it out there and recycle. And recycling the big magnets potentially out of the [worn out] wind turbines*."

4.4 Legitimation

The imperative for a potential UK mission focused on neodymium metal magnets finds unanimous support among interviewees, who identify two key drivers for such a mission: (i) the pivotal role neodymium magnets play in the UK's digital and green transitions, and (ii) the geopolitical implications associated with China's status as the dominant global producer of magnets. These factors collectively underscore the necessity of galvanizing stakeholders to undertake a mission dedicated to neodymium magnets.

The challenge posed by China's near monopoly in the global magnet market is a central concern, as highlighted by an interviewee who noted, "*the dominance of China is the biggest challenge*," emphasizing China's vertically integrated supply chains that span from mining to magnet manufacturing. This integration enables China to maintain cost efficiencies and leverage trade agreements effectively.

In a similar sentiment, another respondent emphasised the significant implications of China's dominance, stating, "*one country, i.e., China, is so dominant that it can control the supply if it wants and when it wants to*". This dominance raises concerns about the potential impact on the supply chain, with scenarios such as restricting raw material exports or controlling magnet prices being highlighted as potential risks.

Corroborating this, our research confirms that a diplomatic dispute between Japan and China in 2011 saw the latter imposing an embargo on the exports of rare earth magnets on the former, sending global prices of neodymium magnets skyrocketing in the early 2010s (Kiggins, 2015; Kalantzakos, 2017). In the mid-1980s, China established its rare earth industry using policies involving subsidies and export rebates (Yan and Zhongxue, 2019). With support from these incentives, coupled with low labour costs and lenient environmental regulations, China achieved a dominant role in the rare earth magnet value chains from mining, through separation, refining and magnet manufacture (see the following figure 4.7).

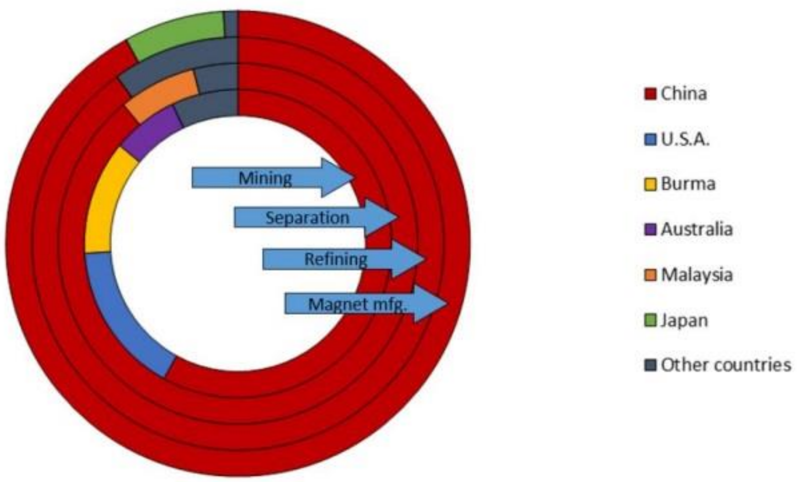

Figure 4.7: Share of top countries in REE processing for permanent magnets, 2019

Source: US Department of Energy (2022)

Rare Earth Elements (REEs) were designated as “protected and strategic minerals,” in China in 1990, limiting foreign companies from mining them. Instead, foreign entities were allowed to process REEs only through joint ventures with Chinese companies, contingent on government approval. The Chinese government further tightened its grip on the industry by implementing export quotas in the early 2000s, progressively decreasing them. In 2005, production quotas were introduced, along with a prohibition on rare earth concentrate exports and an export tax on rare earth oxides and metals, solidifying government control (Andrews-Speed and Hove, 2023).

However, amidst the challenges posed by China’s dominance, interviewees also recognized strategic opportunities for the UK. One respondent pointed out:

> “*by establishing a national mission, we have the chance to create a resilient and sustainable supply chain. This can attract investments, stimulate domestic companies … and secure the UK magnet supply chains*”.

Moreover, integrating circular economy principles into the neodymium magnet lifecycle was proposed to reduce dependence on primary raw materials. “*Investing in recycling technologies is crucial. We should incentivize and support businesses that focus on recycling and repurposing neodymium magnets, thereby reducing our reliance on new raw materials*," emphasized a respondent.

Another key aspect discussed was the need for sustained investment in research and development. Respondents stressed the importance of supporting research initiatives aimed at finding alternative materials for magnets or developing UK capabilities in recycling. “*We need a comprehensive research agenda to explore sustainable alternatives and breakthrough technologies, especially for recycling. This will not only reduce dependence but also place the UK at the forefront of technological innovation*,” suggested an interviewee.

Section 5: Lessons for mission innovation policy and analysis

5.1 Lessons for mission innovation policy

Some recent research has argued that the "perceived time urgency" and "potential big impact" which characterize MIS differentiate them from routine policy interventions (Agarwal, *et al*, 2021). Certainly, MIS will tend to be atypically large, complex, and often time-constrained, a combination of factors which increases coordination challenges and risks and is likely to place significant demands on mission leaders. Do these challenges justify or require new policy practices or are there reasons to follow established best practice in policy development?

For example, the ROAMEF cycle which involves the development of an evidence-based Rationale for intervention, the setting of SMART Objectives, the development and Assessment of a range of policy options and subsequent Monitoring and Evaluation of implemented policies is set out in the so-called Treasury Green Book.[26] While some authors have questioned the use of this approach in practice (Arshed and Drummond, 2020), it remains the UK government's recommendation for best practice in policy development. Moreover, our mission-studies suggest that this type of approach can readily be related to the development of innovation missions, albeit with a significant re-interpretation of the standard approach to policy development.

Figure 5.1 maps the standard ROAMEF cycle onto our episodes/actors framework for mission development (see Figure 1.1). This makes clear the similarity of their underlying logic, albeit with very different underlying settings. Typically, ROAMEF is seen as an idealised policy making process which can guide thinking *within* the public sector. By contrast, developing and delivering innovation missions is likely to require contributions from diverse stakeholders in all episodes from ideation to mission completion and retrospection. This is recognised in Figure 5.1 in the specific contributions to each MIS episode of public sector, private sector, end-users and intermediaries. The need to engage diverse stakeholders in each episode shifts the focus of public policy making towards an emphasis on convening stakeholders, curating knowledge availability, searching for consensus, and building regulatory and incentive structures which can enable innovation. None of this is easy, however, as our mission studies amply illustrate.

Establishing an evidence-based rationale for intervention may be one of the easier steps in mission development. There was wide acceptance of the need for some action from respondents in each of the case studies we considered. In terms of heat pumps it is now widely accepted that climate change must be addressed and the role of gas use in residential settings is well understood. The hydrogen mission was driven by international collaboration but animated by a set of domestic actors working disconnectedly towards similar goals for their own reasons. In terms of neodymium, the resource security and strategic challenges are also widely understood and appreciated.

[26] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent/the-green-book-2020

Figure 5.1: Applying ROAMEF to mission development and delivery

<table>
<tr><th></th><th>Ideation</th><th>Legitimation</th><th>Implementation</th><th>Completion</th><th>Retrospection</th></tr>
<tr><td>Activities</td><td>Formulation of mission objectives, timelines, and nature of challenge,
Provides basis for discussion of objectives and approaches</td><td>Discussion and consultation among stakeholders.
Agreement on mission objectives, timelines, scope, and stakeholder roles.</td><td>Working out of stakeholder roles and co-ordinated action.
Progress towards mission objectives.</td><td>Mission success – full or partial.</td><td>Consultation and capture of learning from mission.
Feedback into improved MIS operations</td></tr>
<tr><td>Rationale</td><td colspan="2" rowspan="3">Public sector – define challenge and evidence base, convening, seek to resolve contested issues and build consensus
Private sector – identify solutions and stakeholders, support mission definition, surface supply chain conflicts
End-users – contribute to problem identification, identify and agree acceptable solutions and ways forwards
Intermediaries- leadership and role modelling for user-led innovation, advocacy, mediation and bridging for contested issues</td><td></td><td></td><td></td></tr>
<tr><td>Objectives</td><td></td><td></td><td></td></tr>
<tr><td>Appraisal</td><td></td><td></td><td></td></tr>
<tr><td>Monitoring</td><td></td><td></td><td colspan="2" rowspan="2">Public sector– set regulatory and incentive structures, knowledge co-ordination and governance, monitor and measure progress
Private – entrepreneurial/innovative input to mission objectives, align activities with mission objectives
End-users – learn to adopt new behaviours/technologies associated with emerging solutions
Intermediaries – knowledge dissemination and education, role modelling of behaviour change</td><td></td></tr>
<tr><td>Evaluation</td><td></td><td></td><td></td></tr>
<tr><td>Feedback</td><td></td><td></td><td></td><td></td><td>Public sector – consultation and capture of learning
Private/End-users – sharing experience of what did and didn't work, adoption of lessons from mission delivery
Intermediaries – knowledge integration and dissemination</td></tr>
</table>

As our mission-studies suggest, a more challenging element of any mission development is developing and building consensus around delivery options. In both the heat pump and hydrogen cases there was little understanding among respondents of the background to the mission objectives, or agreement on their achievability. Policy appraisal can also be challenging, even in the context of a solutions-based mission such as that heat pumps (where the technology is well established). Best practice here suggests that a range of policy options should be identified and then each option should be appraised in terms of its absolute and relative merits. As this example shows there are often different options available; consider for example the use of incentives in England and regulatory measures in Scotland. The relevance of monitoring and evaluation steps in the cycle are also clearly relevant to the heat pump case. The one area where this process might prove challenging in the heat pump case is the requirement to assess policy options in terms of their Net Present Value, which may be problematic in the case of climate change.

The Clean Hydrogen case to some extent also challenges the ability of the UK alone to adopt a ROAMEF type approach given the nature of the international agreement on which the mission target is based. Here, although again the rationale for policy intervention is evident to all, the internal rigour of any national policy process in terms of shaping targets or objectives had to be balanced against the desire to be part of a positive international coalition. This itself is important in making progress towards the targets which again is likely to depend on international research collaboration. The neodymium case highlights similar tensions – international challenges which cannot be met simply by national strategies or missions.

Our mission studies therefore do little to negate the need for adherence to established best practice in policy making. Indeed, in many ways, they reinforce that need for such rigour. This suggests:

- ***The importance of evidence-based policy making*** - The case studies highlight the importance of evidence-based policy making in setting targets, timelines and resource requirements.

- ***The bigger picture*** - Individual missions tend to be one element of a wider programme of policy measures. Targeted policy development needs to be fully contextualised within this wider programme.

- ***Setting realistic and achievable objectives*** - Policy makers seeking to address missions, such as those considered here, face pressures to set objectives that fully address the social need or align with international standards. However, in practice, there may well be a divergence between these requirements and what is realistic and achievable.

- ***Dealing with complexity -*** MIS tend to be highly complex. This is important not least because, in a Hayekian sense, it may well be practically impossible for policy makers to directly manage this complexity[27]. This posits the importance of identifying policy options which negate the need for management *per se*. One policy response to this, has been to engage a wide range of

[27] See, for example, Friedrich von Hayek (1975). "A Discussion with Friedrich A. von Hayek," American Enterprise Institute, number 920817, September.

stakeholders. However, it is far from clear that these stakeholders are better placed to deal effectively with this complexity that the policy makers themselves.

- ***Monitoring and evaluation*** – best practice in policy development suggest that monitoring and evaluation should be included in all policy development. The nature of MIS highlights the importance of clear roadmaps in any future missions.

5.2 Lessons for understanding MISs

The research approach adopted here follows relatively closely that adopted by Wesseling & Mejerhof (2021) although we introduce a framework to elucidate the development of the MIS more clearly through time.

Perhaps the first key lesson is the extent to which ‘missions’ are socially constructed initiatives, involving (at least ideally) agreement between organisations and individuals as to the targets, timelines, and boundaries of the mission. It was evident in the case of heat pumps that this type of agreement between actors was at best partial emphasizing the difficulty of achieving general agreements. International targets with little clear UK-based ‘ownership’ or buy-in also complicate the hydrogen mission. Both place substantial demands on those convening organisations and individuals during the ideation phase of any Mission and on their ability to mediate different perspectives and achieve even partial agreement. Understanding missions requires an understanding of the motivations and capacities of these convening organisations during the ideation phase.

This requirement will differ somewhat depending on the nature of the mission itself. In the case of heat pumps a specific technological solution was being investigated and key issues related instead to relevance (due to the quality of housing stock), production, cost, and installation issues. In other missions the specific technological solutions may be less clear and here, as well as convening power being important in the early critical stages of the mission, co-ordination between STI actors will also be important. Where missions do involve this type of technological search for solutions – as in hydrogen and neodymium - an understanding of the STI actors involved and their capabilities and activities will also be important.

The social nature of missions also focuses attention on their acceptance and relevance to key opinion formers and members of wider society. We therefore include them in our analytical framework although only partially in the earlier account of the heat pumps mission. In future studies this strand of the analysis could be extended significantly using either wider public or social surveys or analysis of media trends and discussion. Both might provide a useful perspective on whether wider society has ‘bought in’ to the relevant mission.

Second, evolution in our own thinking during this first MIS study has emphasized the value of the type of semi-structured interviews which formed our key empirical approach. Generally, these worked well, allowing respondents to provide detailed and highly personalized perspectives. In future studies discussion guides can be developed to reflect our analytical framework (built around episodes) more formally. Interviews with individual actors may also be usefully supported by focus groups with different stakeholder groups.

Thirdly, any account of a MIS such as that provided here, necessarily provides a snapshot at a particular point in time. In terms of heat pumps, we are in 2024 in the ‘implementation’ phase relative to the 2028 installation target. ‘Completion’ and ‘retrospection’ are still to come. In terms of hydrogen and neodymium we are earlier yet in the MIS cycle. This suggests the potential value of a longitudinal approach which can capture the changing roles and interactions between actors as missions develop and move towards completion.

Finally, it is important to recognize that missions do not take place in isolation from the broader social and economic landscape. Current geo-political circumstances – the war in Ukraine and associated fuel cost rises and constraints – illustrate this all too well, changing substantially the economic incentives for the fuel economy. Budget constraints for many households may also make investments in heat pumps and other sustainability activities (e.g., insulation) more difficult. Even where mission actors agree and work in unison therefore, outside circumstances may frustrate mission success. These wider conditionalities will need to be part of any future MIS analysis.

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