The Landscape and Roadmap of the Research and Innovation Infrastructures in Energy

Pourmirza, Zoya; Hosseini, Seyed Hamid Reza; Walker, Sara; Giaouris, Damian; Taylor, Philip

DOI:
10.3390/su14127197

sustainability

MDPI

Article

The Landscape and Roadmap of the Research and Innovation Infrastructures in Energy: A Review of the Case Study of the UK

Zoya Pourmirza [1,*], Seyed Hamid Reza Hosseini [2], Sara Walker [1], Damian Giaouris [1] and Philip Taylor [3]

1 School of Engineering, Newcastle University, Newcastle upon Tyne NE1 7RU, UK; sara.walker@newcastle.ac.uk (S.W.); damian.giaouris@newcastle.ac.uk (D.G.)
2 Scottish and Southern Energy, Perth PH1 3NT, UK; hamid.hosseini@sse.com
3 Department of Electrical & Electronic Engineering, University of Bristol, Bristol BS8 1TH, UK; pvc-research@bristol.ac.uk
* Correspondence: zoya.pourmirza@newcastle.ac.uk

Abstract: Research and development are critical for driving economic growth. To realise the UK government's Industrial Strategy, we develop an energy research and innovation infrastructure roadmap and landscape for the energy sector looking to the long term (2030). This study is based on a picture of existing UK infrastructure on energy. It shows the links between the energy sector and other sectors, the distribution of energy research and innovation infrastructures, the age of these infrastructures, where most of the energy research and innovation infrastructures are hosted, and the distribution of energy research and innovation infrastructures according to their legal structure. Next, this study identifies the roadmap of energy research and innovation infrastructures by 2030, based on a categorisation of the energy sector into seven subsectors. Challenges and future requirements are explored for each of the sub-sectors, encompassing fossil fuels and nuclear energy to renewable energy sources and hydrogen, and from pure science to applied engineering. The study discusses the potential facilities to address these challenges within each sub-sector. It explores the e-infrastructure and data needs for the energy sector and provides a discussion on other sectors of the economy that energy research and innovation infrastructures contribute to. Some of the key messages identified in this study are the need for further large-scale initiative and large demonstrators of multi-vector energy systems, the need for multi-disciplinary research and innovation, and the need for greater data sharing and cyber-physical demonstrators. Finally, this work will serve as an important study to provide guidance for future investment strategy for the energy sector.

Keywords: landscape; roadmap; energy; whole energy systems; energy storage; renewable energy sources; carbon capture and storage; fuel cells and hydrogen; alternative fuels; nuclear energy

check for updates

Citation: Pourmirza, Z.; Hosseini, S.H.R.; Walker, S.; Giaouris, D.; Taylor, P. The Landscape and Roadmap of the Research and Innovation Infrastructures in Energy: A Review of the Case Study of the UK. *Sustainability* **2022**, *14*, 7197. https://doi.org/10.3390/su14127197

Academic Editor: Antonio Messineo

Received: 19 March 2022
Accepted: 9 June 2022
Published: 12 June 2022

1. Introduction

The UK is committed to reducing its greenhouse gas emissions by 2050 to a 'Net Zero' emission [1]. For this to happen, we need to transform the UK economy while ensuring secure, low-carbon energy supplies until 2050. This paper explores the UK's energy research and innovation infrastructure (RII) landscape, which is available for academia and business, and which could contribute vital knowledge for the transition to 'Net Zero'. A roadmap exercise is then undertaken to identify research and innovation challenges, and facilities to address these challenges in energy systems. We, as members of a multi-disciplinary team of the Engineering and Physical Sciences Research Council (EPSRC) National Centre for Energy Systems Integration (CESI), were commissioned by UK Research and Innovation (UKRI) to consult with the energy community and carry out this study. The CESI was established to investigate the potential benefits and risks of greater levels of energy system integration in pursuit of an 80% reduction in greenhouse gas emissions by 2050. This challenge has subsequently become significantly more challenging due to the UK Government's decision to adopt, in 2019, the target of 'Net Zero' greenhouse gas emissions by 2050. In this paper we will demonstrate analysis of the UK's landscape, which was extracted from two questionnaires conducted by UKRI and further supplemented with insight gained from one-to-one interviews, consultation workshops, and further surveys conducted by CESI [2]. We have assisted UKRI to draft reports detailing our findings and recommendations. In carrying out this work, we made a substantial contribution to the preparation of the energy sections of the UKRI Research Landscape and Research Infrastructure reports.

The UK has pursued a research and development strategy which supports the recent Industrial Strategy [3] and four major challenges, which are artificial intelligence and big data, clean growth, the future of mobility, and meeting the needs of an ageing society. Investment is made across technology readiness levels (TRLs) from fundamental research through to demonstration, commercial development, and deployment. Transition from research to deployment is not easy, as evidenced by research on the 'valley of death' [4–8]. Demonstration is seen as a vital stage in moving across this 'valley of death'.

The CESI is to undertake research into the potential for energy systems integration to offer effective opportunities for the energy sector to transition to a low carbon future. Having mentioned this, the fair transition of energy systems incorporates tackling several challenges, including the production and utilisation of hydrogen for decarbonised heat, the retrofitting of low energy efficient UK housing stock, the deployment of digital energy and IoT infrastructure, and ensuring a just transition, especially in relation to vulnerable groups to fuel poverty, to name a few. In order to address these challenges and provide an evidence and basis for making well-informed decisions by policy makers at the national level and local authorities, whole energy systems demonstrators are needed to investigate the possible advantages and drawbacks of possible scenarios for the transition of energy systems among multitude of possible scenarios. In this way, it would be possible to design and evaluate scenarios for the transition of energy systems at local, regional, and national levels, and to achieve the 'Net Zero' carbon targets.

In recognition of the aforementioned value of demonstrators, the project incorporates several full-scale multi-vector energy system demonstrators. These demonstrators can provide data to the research team and enable research concepts to be applied either conceptually or practically. Demonstrators also enable the validation and demonstration of novel future energy system models and scenarios that have been developed for simulation and techno-economic-environmental performance analysis of these integrated energy systems. These models and the dynamic interactions between them can only be developed and trusted through coupling them with advanced experimental emulation and real-world demonstration systems. The key features of these demonstrators are summarised in Table 1.

Table 1. The key features of CESI accessible demonstrators.

Demonstrator	Key Features
Newcastle Helix	Urban, mixed use, new build, multi-vector, data rich
ETI/ESCat Smart Systems and Heat	Urban, domestic, retrofit, heat and power
Findhorn	Eco village, socio technical
Haringey	Socio technical urban living laboratory
Thames Valley Vision	Industrial and commercial demand response
Cockle Park Farm	Rural, farming, anaerobic digester, heat and power
Customer Led Network Revolution (CLNR)	Storage, smart grids, suburban, rural, medium and low voltage

The energy trilemma is at the heart of the evaluation of benefits and risks i.e., security, affordability and access, and sustainability [9–11] Through interdisciplinary research and collaboration, CESI seeks to gain a deeper understanding of how to achieve a just transition to 'Net Zero'. Therefore, when considering benefits and risks, CESI takes care to consider how they are distributed across society, industry, and governments, and when they may occur.

Overview and Project Scope

The UKRI was commissioned by the UK Department of Business, Energy and Industrial Strategy (BEIS) to undertake a programme of study to develop a RII roadmap. The UKRI is a quasi-autonomous non-governmental establishment that leads research and innovation funding in the UK, by bringing together seven research councils, Innovate UK, and Research England. This RII roadmap programme was aimed to enhance understanding of UK's current capability and innovation infrastructure and provide a pathway for future planning. Additionally, this study aimed to develop a roadmap to boost financial contribution in R&D (research and development) to 2.4% of GDP (gross domestic product), and within the UKRI to develop its roadmap strategy [2]. The CESI group was commissioned by the UKRI to undertake the energy sector study of this programme.

The UKRI programme has been structured and made recommendations across the six sectors used by the ESFRI (European Strategy Forum on Research Infrastructures) to support the setup of exercise and to ensure that the UK remains a global leader. These six sectors are as follows: biological sciences, health and food (BH&F), energy, environment (ENV), physical sciences and engineering (PS&E), social sciences, arts and humanities (SSAH), computational, and E-INFrastructure (E-INF).

In this study, we only focused on the energy sector. Drawing on the findings from our study on this sector, we enrich the programme-wide explanation of research infrastructures in order to include the following sub-sectors: whole energy systems, energy storage, renewable energy sources, carbon capture and storage, fuel cells and hydrogen, alternative fuels, and nuclear energy.

In the rest of this paper, we will only investigate the energy sector along with the aforementioned seven energy sub-sectors. We will explore the existing energy RIIs and concerns around them. Next, we will present the analysis of the survey, such as links between the energy sector and other sectors, distribution of energy RIIs across the UK, the age of energy RIIs, where most of the energy sector infrastructure is hosted, and the distribution of energy RIIs according to their legal structure. We will then investigate the roadmap of research and innovation infrastructure in energy by 2030, by identifying challenges in each of the seven sub-sectors, and facilities to address these challenges within each sub-sector. Finally, we will discuss the e-infrastructure and data needs of the energy sector.

2. Methodology

In this study, we aimed to create a long-term research and innovation infrastructure roadmap based on an understanding of existing UK infrastructure, future needs, and resulting investment priorities. We used a number of methodologies to carry out this study. In this work we have collected both qualitative and quantitative data, and individual data and group data. This section consists of two phases which are used for two distinct activities, namely, creating a landscape and developing a roadmap. The first phase aimed to create the current RII landscape, and discusses methods used to develop this landscape. The second phase aimed to develop the RII roadmap by identifying subsectors of the energy sector, their challenges, and potential RII facilities to address these challenges. Phase two discusses methodologies used to develop the RII roadmap.

2.1. First Phase

In the first phase of the study, the focus was on the RII existing landscape. In order to identify the current RIIs in the energy sector, four main tools have been used.

2.1.1. UKRI Survey

Two surveys were carried out by UKRI from the RIIs in all the sectors. Out of all the 755 responses received, 26 RIIs were performing research predominantly in the area of energy and this formed the survey sample.

2.1.2. Interviews

Key individuals (more than 100 experts) in various sub-sectors of energy from government, academia, and industry across England, Scotland, and Wales were identified by UKRI and CESI based on their expertise and experience in energy systems, and they were contacted. One-to-one interviews with these key individuals were conducted based on the following themes:

- What the current RII are (both in the UK and abroad);
- Who the stakeholders are;
- What the risks/mitigating mechanisms are.

2.1.3. Expert Elicitation Workshops

Several workshops were organised in London and Edinburgh with 116 attendees in total. The workshops were facilitated by the 'Knowinnovation' scientific facilitator team and were structured using a professional facilitator tool called 'Well sorted'. Prior to the workshop, a set of questions were sent to various experts via the Well Sorted tool, and participants were asked to submit their ideas. Then, Well Sorted clustered the individual ideas into thematically similar groups, which served as a starting point of the workshops. Workshops then collated the participant collective views regarding the themes which had emerged from individuals.

2.1.4. Review of the Literature

The following documents were investigated as the main source of information in order to identify RIIs:

- RCUK Energy programme Strategy Fellowship reports [12];
- UKERC Landscape reports in energy;
- HM Government report on the nuclear research landscape [13];
- Energy System Catapult report on the energy sector research facilities and demonstrators [14];
- EPSRC report on the Scale and Scope of Academic energy research in the UK [15].

Figure 1 demonstrates the overall process of the phase 1 methodology to create the landscape of energy RII in the UK.

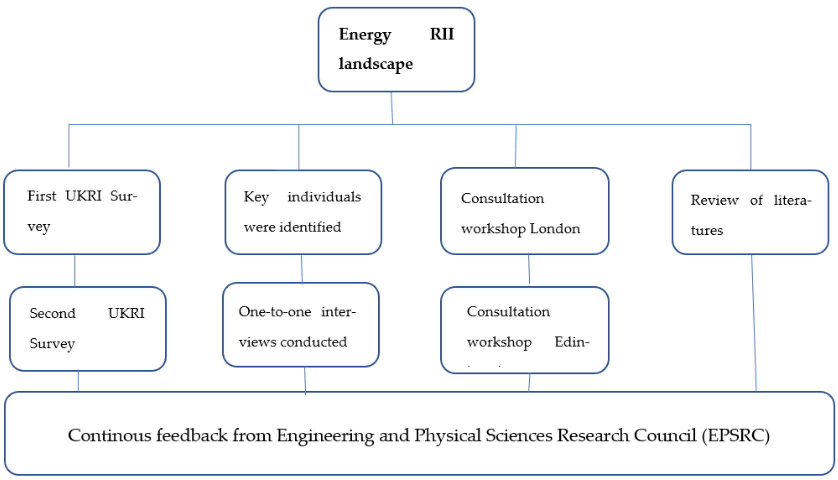

Figure 1. Phase 1 methodology to create the energy RII landscape.

2.2. Second Phase

In the second phase of the project, in order to identify the need and roadmap for RIIs in the energy sector, two main methodologies have been used.

2.2.1. Interviews

Key individuals in various sub-sectors of energy from academia, industry, government, hubs, and catapults from across England, Scotland and Wales were identified and contacted. These energy experts included individuals from the UK Government (17), UK universities (56), industry (9), the Marine Supergen Hub (1), UKERC (1), the Transport System Catapult (1), ETI (1), the Energy Systems Catapult (2), the Offshore Renewable Energy Catapult (1), the Energy Research Accelerator (5), the European Marine Energy Centre (1), the Renewable Energy Association (1), and the Nuclear Innovation and Research Office (1). One-to-one interviews with these key individuals were conducted based on the following subjects:

- What the future research challenges are;
- What future RII needs might be (including who might build/operate them);
- Who the stakeholders are;
- What the risks/mitigating mechanisms are.

2.2.2. Workshops

In line with the landscape exercise, we organised several workshops in London using a professional facilitator from 'Knowinnovation'. A set of questions were sent to experts' several weeks before the events, and their replies were processed and served as a starting point at the workshops.

Table 2 shows the number of participants in each event, and categorises them into academic, non-academic, and government sectors. It shows that this study was informed by collating information from 242 experts in energy system, comprising of 126 one-to-one interview and 116 workshop participants.

Table 2. Number of participants in each event.

	Academic	**Non-Academic**	**Government**	**Totals**
One-to-one interview and online survey	79	31	16	126
Phase 1 consultation workshop 1 (London)	29	5	2	36
Phase 1 consultation workshop 2 (Edinburgh)	16	6	1	23
Phase 2 workshop 1 (London)	16	11	2	29
Phase 2 workshop 2 (London)	17	7	4	28
Total	**157**	**60**	**25**	**242**

Finally, feedback from the Engineering and Physical Sciences Research Council (EPSRC) during both phases helped to improve and refine the interview and workshop approaches.

Figure 2 demonstrates the overall process of the Phase 2 methodology to create the roadmap for energy RII in the UK.

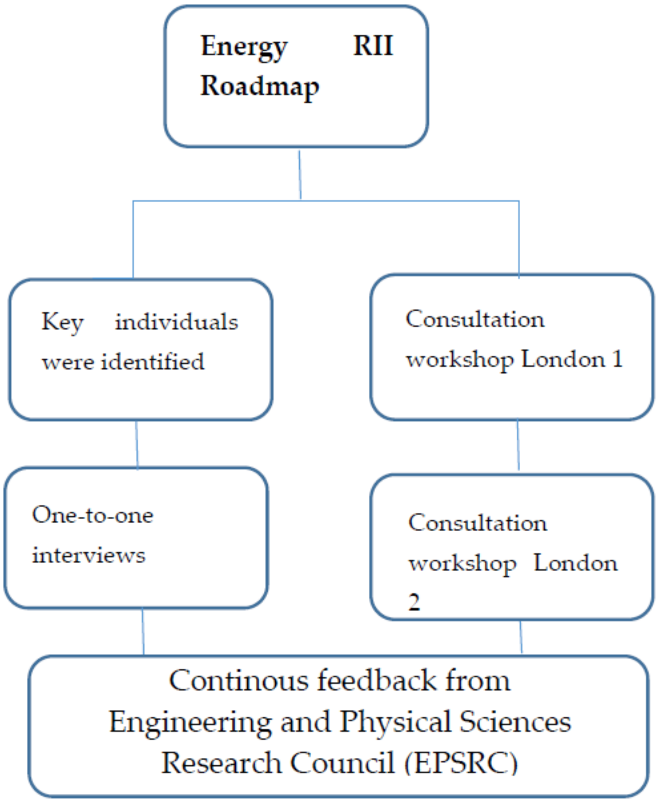

Figure 2. Phase 2 methodology to create the energy RII roadmap.

3. Current Landscape of Research and Innovation Infrastructure in Energy: Phase 1

The UK has a long history of providing funding through public/private means and charity to build a world-leading research and innovation infrastructure. In this research we will consider only public funded infrastructures from organisations, such as UKRI and its councils, other government departments and devolved administrations, and public sector organisations. We have considered large and costly infrastructures physically located in the UK or overseas which can provide regional or national capability, or the infrastructures that are digitally accessible. The UKRI believes this is the first time that an exercise of this breadth and type has been attempted in the UK [2].

3.1. Current Landscape Study Based on Review of the Literature

Several publicly available documents and reports on the analysis of the current landscape of energy RIIs in the UK were studied in order to capture all the available energy RIIs. These documents, which inform this paper, encompass previous works/projects in order to obtain insights from them and build on top of the available knowledge. These documents and reports include the RCUK Energy programme Strategy Fellowship reports, the UKERC Landscape reports, the HM Government report, the Energy System Catapult report, and the report on the scale and scope of academic energy research in the UK. Table 3 summarises the current landscape of energy RIIs in the UK that were explained in the reviewed previous documents/reports. As can be seen, the RIIs are classified into several energy themes as follows: (i) whole energy systems; (ii) buildings; (iii) power systems; (iv) energy system demonstrators; (v) nuclear; (vi) carbon capture and storage (CCS); (vii) renewable energy sources; (viii) alternative fuels; (ix) hydrogen; and (x) energy technologies & markets.

Table 3. Current landscape of UK energy RIIs in reviewed available documents.

Energy Related Area	Energy RII(s)
Whole energy systems—interdisciplinary research	• The Centre for Renewable Energy Systems Technology (CREST) • The Tyndall Centre for Climate Change Research
Buildings	• Building Research Establishment (BRE) • Salford Energy House
Power systems	• The Tony Davies High Voltage Laboratory (TDHVL) • The Power Network Demonstration Centre (PNDC) • The National Grid Power System Research Centre, including the High Voltage and High Current Test Laboratory • The High Power Laser Energy Research facility (HIPER)
Energy system demonstrators	• The Integrated Transport Electricity and Gas Research Laboratory (InTEGReL) • The Keele Smart Energy Network Demonstrator (SEND)
Nuclear	• The Culham Centre for Fusion Energy (CCFE), including the Joint European Torus (JET) and Mega Amp Spherical Tokamak (MAST) • ORION • The National Nuclear User Facility (NNUF), including the Microscope and Ion Accelerator for Materials Investigations facility (MIAMI) • The Dalton Cumbria Facility (DCF) of Manchester University • The Nuclear Advanced Manufacturing Research Centre (AMRC) • The National Nuclear Laboratory
CCS	• The Peterhead Carbon Capture and Storage (CCS) Project
Renewable energy sources	Wind • The National Renewable Energy Centre (Narec) • The Energy Technology Centre (ETC) • The Hunterston Offshore Wind Turbine Test facility Marine, wave and tidal • The European Marine Energy Centre (EMEC) • The Marine Renewables Test Centre • The Peninsular Research Institute for Marine Renewable Energy (PRIMaRE) • The FloWave Ocean Energy Research Facility • The Offshore Renewable Energy Catapult, National Renewable Energy Centre • Wave Hub Ltd. Solar • The NaREC Photovoltaic Technology Centre (PVTC) • The Centre for Solar Energy Research (CSER) • The Low Carbon Research Institute (LCRI)
Alternative fuels	• The European Bioenergy Research Institute (EBRI)
Hydrogen	• The Renewable Hydrogen Research and Development Centre
Energy technologies & markets	• The Energy Centre Thornton Science Park

3.2. Current Landscape Analysis Based on UKRI Survey

In this section, we provide an overview of publicly funded energy RIIs in the UK. The current picture of the landscape of the energy RIIs is collected based on the expert consultation workshops, UKRI and CESI surveys, interviews, and the current study based on the literature review. These are presented in Table 4. It is revealed that energy sector has a relatively small group of infrastructures comparing to other sectors, but due to the interdisciplinary and multidisciplinary nature of the energy sector a large number of infrastructures in other sectors would address the underlying science and challenges of the energy sector [16]. The list of existing energy infrastructures can be found in Appendix A.

Table 4. Landscape of the Energy RIIs in the UK.

Area of the Energy Infrastructure (in the UK)	Responded to UKRI Survey	Identified by CESI [1]	Total
Whole energy system			
• Interdisciplinary	1	3	4
• Gas turbine	1	0	1
• Building	2	2	4
• Energy models	1	0	1
• Oil and gas	1	0	1
Power systems	0	5	5
Energy system demonstrator	1	1	2
Nuclear	3	4	7
Carbon capture and storage	1	1	2
Energy storage	3	0	3
Renewable energy sources			
• Wind	1	4	5
• Marine	3	5	8
• Solar	0	3	3
• Geothermal	0	0	0
Alternative fuels	2	2	4
Hydrogen	0	1	1
General infrastructures	6	1	7
Total	26	32	58

[1] Identified by CESI team through workshops, interviews, and key reviews, and not currently captured by the questionnaires.

The coverage of areas where energy RIIs strongly participated in the survey are whole energy system, CCS and alternative fuels, energy storage, and energy system demonstrators. Energy RIIs with poor coverage include power systems and wind and solar renewable energy sources [16].

In the rest of this section, we will present the analysis of the UKRI survey. Figure 3 depicts the links between the energy sector and other sectors. Twenty-six of the infrastructures which responded to the survey recognised energy as their primary sector. These energy RIIs have the greatest linkage with the environmental and PS&E sectors, and less significant linkage with BH&F, SSAH, and e-infrastructure. In Figure 3, the peripheral nodes depict the other sectors, and their size represents the proportion of their linkage with the energy sector [16].

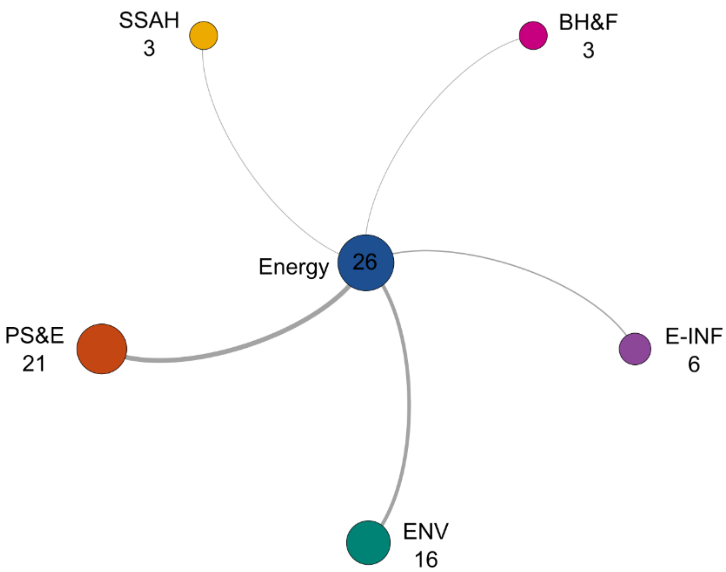

Figure 3. Interdisciplinary working between infrastructures that identified energy as their primary sector and other infrastructures.

Additionally, 51% of the remaining infrastructures which identified other sectors as their primary sector recognised a linkage between their sector and energy sector. These results prove the strong link between energy and other infrastructure sectors.

The infrastructures that declared energy as their primary sectors have a strong link to other sectors. This study reveals that 73% of such energy RIIs can be strongly linked to the environmental sector, such as the ECCI (Edinburgh Centre for Carbon Innovation), and Ergo (East Riding of Yorkshire Council). Additionally, about 71% of energy RIIs are linked with the PS&E sector or have considered PS&E as their sub-domain, such as SPECIFIC (the Sustainable Product Engineering Centre for Innovative Functional Industrial Coatings) and the NNL (National Nuclear Laboratory). Finally, there exist energy RIIs that cover both the environmental sector and the PS&E sector, which include PACT (Pilot-scale Advanced Technology) and PRL (Pyrochemical Reprocessing Laboratory). Figure 4 shows the distribution of linkage between energy RIIs and other sectors. These linkages are mostly evident between the energy sector and PS&E, environmental, and computational and e-infrastructure sectors.

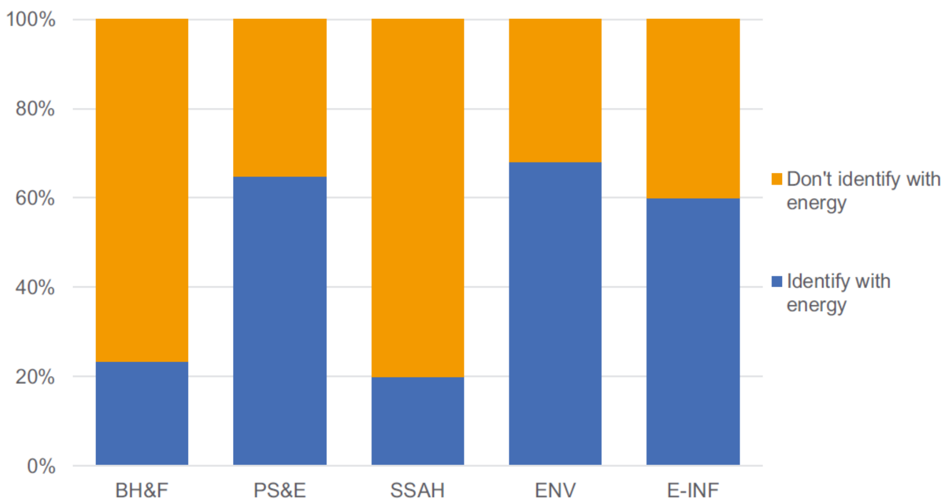

Figure 4. Distribution of infrastructures that are linked with energy sector.

Figure 5 shows the distribution of energy RIIs across the UK. This graph is a contour map depicting the Midlands as the area of greatest density of energy RIIs. However, due to the overall small sample size and corresponding large contours, a fairer analysis is that facilities are quite scattered throughout the UK [16]. Red dots indicate individual infrastructures or clusters at one location identified through the UKRI questionnaire, whereas black dots indicate individual infrastructures or clusters at one location identified through other means. Furthermore, red areas indicate the highest overall densities, and blue areas indicate the lowest overall densities, with smoothing applied across contours.

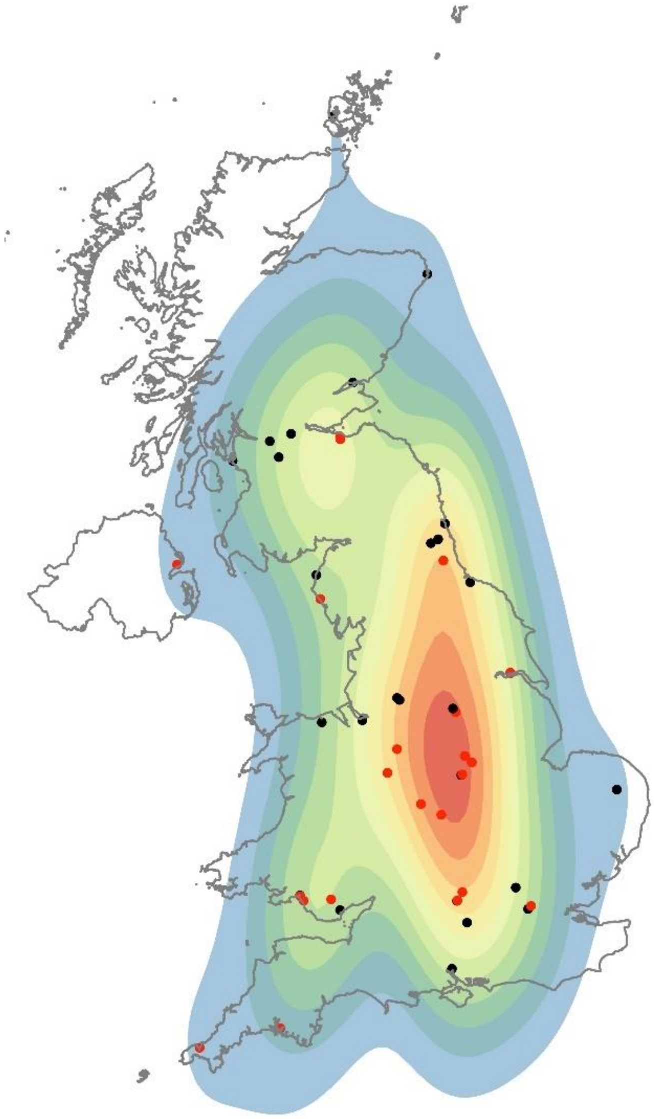

Figure 5. Distribution of energy RIIs across the UK.

Figure 6 presents an overview of the age of energy RIIs. This figure shows that a vast majority of the energy RIIS are relatively new, with 85% starting operations within the last 15 years. This young age of energy RIIs could be because of the increased investment in energy over the last 15 years in response to energy challenges. For instance, since 2004 UKRI energy programme spend has risen from £30 million yearly to £180 million yearly. The Energy Technology Institute (ETI) was established in 2008, which had a budget of up to £100 million per year for 10 years and was equally funded by public and private sectors. Simultaneously there was a rise in energy research and development (R&D), supported by BEIS, and the UK promised to double energy research and development to £400 million each year [17].

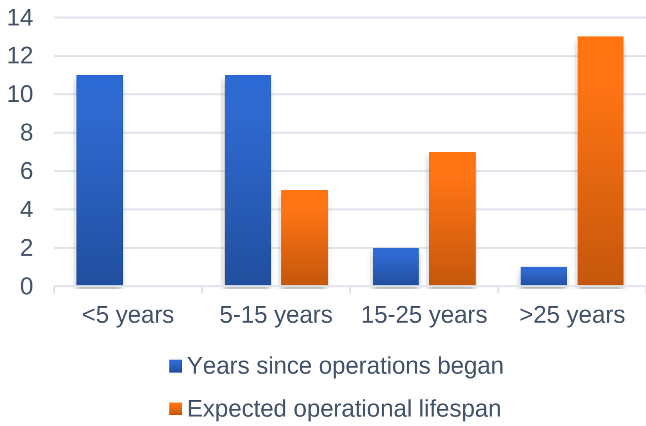

Figure 6. Infrastructures grouped according to their years of operations and their expected operational lifespan.

Figure 7 illustrates whether these RIIs are single entities, grouped/distributed entities, or virtual. This study reveals that about 77% of energy RIIs are single-site physical entities. Interestingly, these numbers are again higher than most of the other sectors. The survey shows that most of the energy RIIs are accommodated within other organisations which are dependent on long term funding, such as universities. Generally, the smaller and more highly focussed facilities are hosted in universities. These centres can offer underlying scientific capability. An example of one such energy RIIs is the FloWave Marine Test Facility in Edinburgh University. Other facilities, which would provide services to a particular large market or address a unique challenge, can act as a single energy RIIs, e.g., the National Nuclear Laboratory (NNL). Single-site RIIs deal with highly specific challenges or help to address a particular market which is big enough to permit research in only one energy area. However, in some cases, it is not economically efficient to have a dedicated energy RII. In these cases, large centres are created which are distributed across all sectors. Additionally, when demand and expertise are distributed, distributed infrastructure can help avoid the relocation and duplication of facilities. An example of distributed RIIs is the National Nuclear User Facility (NNUF), funded by EPSRC, with the aim to develop a multi-site facility and enable industry and academia to access internationally-leading experimental equipment.

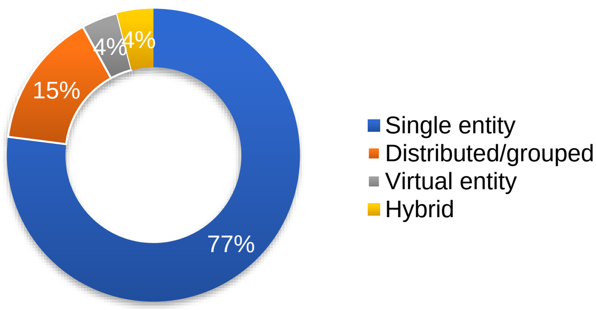

Figure 7. The distribution of RIIs according to whether they are single entities, grouped/distributed entities, or virtual.

Figure 8 illustrates the distribution of energy RIIs according to their legal structure. The study shows that 19% of the energy RIIs are national or international legal entities, which is a slightly higher portion of national and international legal entities compared to other sectors. Energy RIIs that contribute to the UK's international responsibilities include facilities within UKAEA, such as Joint European Torus (JET), which is the biggest magnetic fusion experiment in the world and the biggest EU facility in the UK [16]. Additionally, 12%

of energy RIIs are accommodated in another organisation with short-term funding, while 69% of energy RIIs are accommodated in another organisation with a long-term facility.

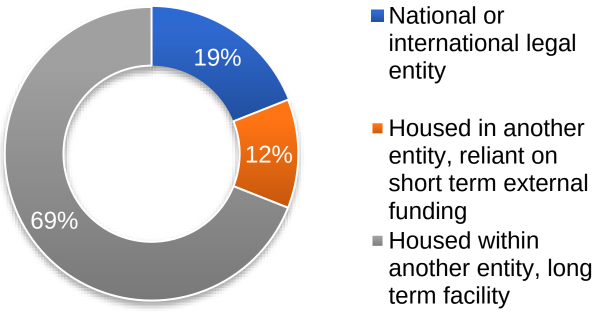

Figure 8. The distribution of RIIs according to their legal structure.

The energy RIIs primarily contribute to sectors including the energy supply chain and utilities. The other top sectors of economy that energy RIIs contribute to, as depicted in Figure 9, are as follows: public policy, transportation, manufacturing, instrumentation, and construction. Therefore, this figure indicates the importance of energy RIIs in terms of economic contribution, and their critical role in reducing carbon emission and meeting government carbon targets.

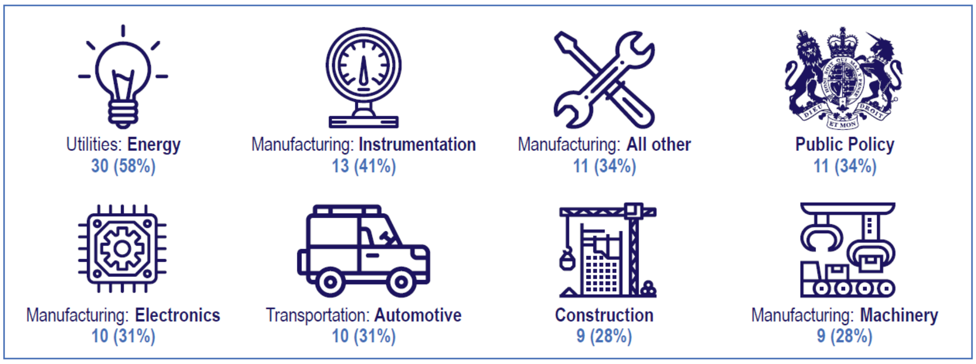

Figure 9. Top eight sectors of the economy that energy RIIs work with or contribute to (excluding research and education).

This survey also identifies a number of barriers to the effective operation of energy RIIs and the mitigation strategy. The barrier or concerns to maximise the value of infrastructures are as follows: certainty of funding and the period of available funding, Brexit and its uncertainty, and lack of personnel/experts and key skills. The strategies to ease these concerns are to broaden the funding area, collaborative work, and providing staff training and more recruitment [16].

It is believed the UK energy system is expected to undergo significant transition. While it is uncertain what the future landscape for the energy system might be in detail, and which energy resources will dominate, it is evident that the future energy system will be more intelligent and connected, and that it will require more co-ordination between different energy resources. Given the fact that the energy system is transitioning into a smarter and more connected system, the UK is enhancing its capabilities in smart metering, connected devices, data, technology, modelling, and simulation, which are required to comprehend the impact of these changes and develop enabling technologies to realise these changes. Furthermore, UK universities are hosting these capabilities, which are developing new technologies and creating new energy system models. Currently, institutions, such as the Energy Systems Catapult, are facilitating collaboration between UK academics, industries, and the government in order to accelerate the UK energy system transformation.

4. Roadmap of Research and Innovation Infrastructure in Energy by 2030: Phase 2

In this phase a number of subsectors for the energy sector, along with their potential RII facilities, are identified in this study. These subsectors are as follows:

- Whole energy systems;
- Energy storage;
- Renewable energy sources;
- Carbon capture and storage;
- Fuel cells and hydrogen;
- Alternative fuels;
- Nuclear energy.

In this study we have identified challenges, as well as facilities to address these challenges, within each sub-sector through consultation with the experts in this field, as explained earlier. The potential required RIIs and the scientific, research, and/or innovation (SRI) challenges for every RII in each subsector are presented. Through our surveys and interviews we consulted with experts to filter each item based on medium and high strategic importance.

4.1. Challenges and Capability Requirements of Subsectors

4.1.1. Subsector 1: Whole Energy Systems (Including Demand and Networks)

The experts identified a number of challenges in whole energy systems and possible capabilities to address these challenges. Table 5 depicts the science, research, and/or innovation challenges of the whole energy systems subsector and potential RIIs.

Table 5. Presents the science, research, and/or innovation challenges of the whole energy systems subsector and potential RIIs.

Science, Research, and/or Innovation Challenge	Potential Capability Required
To model whole energy system, in order to comprehend the cyber and physical consequences of decarbonizing heat, power, and transport	A Centre of Excellence for Energy Modelling, performing as a platform for nationally significant models Labs and facilities that join the physical and cyber components of a multi-vector energy system
To optimize the control, investment, architecture, and cross vector interaction of energy systems	Living lab demonstrators coupled with a pipeline of innovation, data capture and analysis, market development, and considering the socio-techno-economic impact
Digital twins of multi-vector energy system	Simulation for cyber-physical energy systems, together with the high-performance computing, cyber-physical models, and sensors
Heat decarbonizing	Distribution network demonstration to investigate the district heating, heat electrification, and repurposing the hydrogen

4.1.2. Subsector 2: Energy Storage

The experts identified a number of difficulties in the energy storage sub-sector and proposed solutions to resolve the raised issues. Table 6 depicts the science, research, and/or innovation challenges of the energy storage subsector and potential RIIs.

Table 6. Presents the science, research, and/or innovation challenges of the energy storage subsector and potential RIIs.

Science, Research, and/or Innovation Challenge	Potential Capability Required
To develop economical energy storage for thermal (heat/cooling), electrical energy, and demand at a considerable size	Test beds to enable different technologies of energy storage to be tested and expanded across various applications, such as grid-scale, generation-integrated, domestic, neighbourhood area, distribution networks
Flexible storage of conditions in living lab	Large living labs for different archetypes including suburban, urban, industrial, and mixed Capabilities and resources for social science research for energy storage, focusing on extensive consumer research and change studies
To integrate energy storage alongside wind energy generation	Testing platform for wind turbines, in which technologies used in energy storage can be experimented to show their potentials to store excess electricity thermally, chemically, and kinetically in batteries
Emerging/new materials or technologies	Advanced material testing platform, characterization, and synthesis

4.1.3. Subsector 3: Renewable Energy Sources

The experts identified a number of difficulties in the renewable energy sources subsector and proposed solutions to resolve these issues. Table 7 depicts the science, research/innovation challenges of the renewable energy sources subsector and potential RIIs.

Table 7. Potential RIIs and science, research/innovation challenges of the renewable energy sources subsector.

Science, Research, and/or Innovation Challenge	Potential Capability Required
Environmental study and social science investigation for printed photovoltaics (PVs), assisting the scale up and financial interests	A national centre for economical printed PV assisting the UK distributed research community and connecting manufacturing and adoption
Studying large-scale tidal stream/wind/wave energy extraction and its interaction with the environment	Large-scale laboratory for wind-wave-current combined basins and measurement systems (fully instrumented at-sea demonstration sites)
Advancement for UK geothermal capabilities. Unique UK geo-energy observatory capabilities should substantially improve underpinning subsurface geothermal science, along with further energy areas. Extra capability in this area is required because of its national importance, particularly once the technology enter the development phase	Facilities (medium to large) to investigate primary research on geothermal energy co-production, potentially accompanied by gas and oil production
Tackling operational issues essential to inertia reduction of the energy system as a result of great penetration of renewables	Test bed with asynchronous inertia shafts, such as the ones in wind turbines, aimed at testing methods to include inertia in the electricity system

4.1.4. Subsector 4: Carbon Capture and Storage

In order to investigate the SRI challenge of the CCS, experts proposed a number of solutions, and discussed difficulties and challenges in CCS industry. Table 8 depicts the science, research/innovation challenges of the carbon capture and storage subsector and potential RIIs.

Table 8. Potential RIIs and science, research/innovation challenges of the carbon capture and storage subsector.

Science, Research, and/or Innovation Challenge	Potential Capability Required
The way CCS infrastructure merge with the overall energy system	Test bed facility to determine how CCUS withstand changes in demand with the use of component testing in the CCS chain, a CO_2 storage trial test bed, a combustion/hydrogen production experimental scale facility, and a CO_2 transport facility
Decarbonization method for heavy industry with CCUS (carbon capture, utilisation, and storage)	Synchronized facilities linking together to show next generation capture and utilisation technologies Optimising amine scrubbing, at a scale of equal to 1–10 MWe. This could be considered as an important link from small pilot plants to full-scale demonstrators. On a minor scale, these linked facilities should embed arising next generation capture technologies that shall progress via pilot-plants operating at a scale of ca. 50–500 kWe
Determine less carbon generation with CCUS	Pilot scale capabilities to bridge the gap between fundamental study and analysis with commercialization, and link these together (TRL3-6)
Investigate CO_2 within the storage capability, and CO_2 reaction to the host rock and the underground biology	A demonstration embedding CCS within energy system. A 'borehole lab' is required, with an array of boreholes, instrumentation, and research capability

4.1.5. Subsector 5: Fuel Cells and Hydrogen

The experts identified a number of difficulties in the fuel cell and hydrogen sub-sector and proposed solutions to resolve the raised issues. Table 9 depicts the science, research, and/or innovation challenges of the fuel cells and hydrogen subsector and potential RIIs.

Table 9. Potential RIIs and science, research, and/or innovation challenges the of fuel cells and hydrogen subsector.

Science, Research and/or Innovation Challenge	Potential Capability Required
Utilisation of hydrogen and safety devices	A centre of excellence for hydrogen utilisation funded by manufacturers with networks to advance and share the lessons learned
Mass generation of low carbon, cheap, resilient hydrogen	A demonstrator for low carbon hydrogen production to show hydrogen can be produced and supplied at low cost. This could be the source to the commercial market.

Table 9. *Cont.*

Science, Research and/or Innovation Challenge	Potential Capability Required
Hydrogen utilisation in the gas network, either as 100% hydrogen or mixture	Research and development and demonstration to repurpose the gas grid (TRL 5-8), fuel cell research (TRL 6-8), gas storage (TRL 3-6), combustion (TRL 6-8)
Exploring and responding to difficulties in underground storge of hydrogen	Capabilities or laboratories with an array of boreholes, and also hydrogen storage, pipework and measurement equipment
Performance enhancement and decreasing the price of fuel cells	R&D capabilities which can investigate research and development of hydrogen economy and has the potential to develop fuel cells technology

4.1.6. Subsector 6: Alternative Fuels

The experts identified a number of difficulties in the alternative fuels sub-sector and proposed solutions to resolve these issues. Table 10 depicts the science, research, and/or innovation challenges of the alternative fuels subsector and potential RIIs.

Table 10. Potential RIIs and science, research/innovation challenges of the alternative fuels subsector.

Science, Research, and/or Innovation Challenge	Potential Capability Required
Every element of the biofuels value chain Improved linkage amongst fuel chemistry and its characterisation properties (e.g., together with pollutant emissions)	Interdisciplinary laboratory for alternative fuels considering chemistry, mechanical engineering, and agriculture Academic capabilities (virtual) connected via a central capability
Zero emissions vehicles (in addition to cars, other vehicles such as large vehicles, and non-automotive sectors, such as aviation or marine, and diesel generators)	One main centre to explore and strategize alternative fuels options. A research hub (similar to the Faraday Institution) enabling research and delivery for alternatives options
Mapping of organic waste availability and evidenced-based life cycle analysis work to investigate the environmental impact of current systems against the possible savings of utilizing anaerobic digestion (AD)/biorefineries in urban/agricultural situations	A 'virtual centre for AD' with a supportive and collaborative research programme together with industry and academia
Combustion and conversion	Essential trial equipment, which is instrumented, in order to deliver a controlled environment which is required for improving the knowledge of biofuel combustion behaviour and the comprehending its impact on the internal combustion engine

4.1.7. Subsector 7: Nuclear Energy

The experts identified a number of difficulties in the nuclear energy sub-sector and proposed solutions to resolve these issues. Table 11 depicts the science, research/innovation challenges of the nuclear energy subsector and potential RIIs.

Table 11. Potential RIIs and science, research, and/or innovation challenges of the nuclear energy subsector.

Science, Research and/or Innovation Challenge	Potential Capability Required
Establish nuclear engineering capabilities that are required for supporting the upcoming new build programme, especially in system engineering	An engineering centre of excellence for nuclear energy is needed, to enable nuclear energy engineering from multiple disciplines to share scientific capabilities. Demonstration sites are required to support the Catapults' agenda/programme of work
Nuclear legacy management (high, intermediate and low level of waste, nuclear logistics, and decommissioning technology)	Capabilities for managing and examining active materials, better engineering and expansion. Capabilities for designing and developing management technologies, treatment, and waste minimisation for active and non-active environments Capabilities for drawing on huge advances in retail logistics via utilizing distributed digital systems (e.g., distributed control systems used in nuclear power plants). These enable better performance of the system, since they utilize various technologies, such as advanced HMIs (human system interfaces), improved diagnostics and maintenance, and bus technology
Fission: Prospective fuels needs of prospective nuclear reactors (AMRs, GenIII+, Gen IV, SMRs)	Capabilities for developing and examining prospective fuels, inclusive of accident tolerant fuels. Preserving and expanding UK advanced fuel competency is required for current and prospective reactors, both defence and civil
Fusion: Plasma control (heat management, superconducting magnets, and machine geometry)	Huge fusion reactors are needed to help and promote the study of plasma control, fusion, and superconducting magnet technology. A test bed and lab for a spherical tokamak suitable for generating electricity
Facilitate following services in nuclear reactors: robotic maintenance, health monitoring, and high heat extraction.	Thorough and broad conceptual design centres to provide the following investigation and study for nuclear energy: high heat flux, material study, robotic maintenance, and component testing.
Improved thermal transfer from reactor to electricity generation systems.	A thermal hydraulic research and test facility
Advanced reactor understanding and development.	Demonstrators and labs which support the design capability understanding in the UK. These provide the informed assessment and development of prospective reactor designs, and also operation and regulation of these facilities.
Several nuclear plants in the UK are about to be decommissioned, which will cause the following serious challenges: clean-up of a previous nuclear plant sites safe, extended storage and disposal of spent nuclear fuel and decommissioned nuclear plants wastes	A demonstrator and lab to assess the containment technology, geo-barriers and host rock properties/interactions with the stored waste. A capability for environmental remediation

5. Links to E-Infrastructure and Data Needs for Energy Sector by 2030

E-infrastructure could offer a number of services to energy systems by providing data which are a valuable resource used to inform models, inform policy interventions, enhance the forecasting precision, improve the cost, and assist in the growth of businesses. The need to ensure that services are provided successfully, demands a much richer information and communication technology (ICT) monitoring and control network than the current system [18]. E-infrastructure contains a variety of data formats and data sources to meet different needs, such as systems performance and control data required to preserve grid stability, weather data to predict peaks and troughs in electricity production, and market data to guarantee optimum efficiency for suppliers and consumers. Smart energy systems should be digitally connected to allow the information, models, and results to be exchanged within the systems, and outside the energy systems, such as in national critical infrastructure. An inappropriate or less sufficient exchange of data and models will result in the whole or part of energy system not being monitored, modelled, and finally controlled.

E-infrastructure is responsible to simulate the entire energy system and ensure the security of the system is preserved. It can also provide early detection of faults or errors, and real-time monitoring of distant services and capabilities (such as wind farms) which is useful for performance examination. Such e-infrastructure addresses a number of challenges in the energy sector, including recording data, carrying out complicated modelling, and simulation of a number of subsectors/subsystems.

The result of the survey run by UKRI shows that three quarters of energy RIIs believe that within 5 to 10 years, e-infrastructure and data will become more important. Additionally, the survey demonstrates that two thirds of energy RIIs report a 'significant e-infrastructure/data requirement or component'.

E-infrastructure is facing upcoming challenges for future energy system, such as the incorporation of diverse and new data types and data sources. These may bring difficulties in terms of data storage, data communication [19], data interoperability, cyber-interdependencies [20], missing data treatment [21], and coordination of security policy, that could be mitigated by studying in the bridges and connectors amongst energy sector and computational and e-infrastructure. Additionally, e-infrastructure of energy system suffers from cyber security challenges caused by interconnectivity between sensors and controllers. The majority of devices installed, and communication protocols used in the energy grid, are designed with limited cyber-security considerations, which would increase the risk of economic loss, asset damage, or widespread blackouts [22,23]. Furthermore, the data captured and stored in e-infrastructure are considered as valuable assets and should be protected as an asset of the company and the property of the individual customer.

Finally, e-infrastructure can play a significant role in achieving whole energy system optimisation, control, prediction, and management [24]. E-infrastructure can use a sensor-enabled digital replica of the energy system to enable a digital twin for the entire energy system [25]. It can also enable the development of innovative business models or adaptation of such new models [26,27]. Therefore, the integration of e-infrastructure and energy RIIs can improve the capability of multi-sector and multi-vector energy system development.

6. Discussion

The emerging themes discussed in this paper are part of industrial strategy and priority sectors for government policy. Collaboration between researchers in academia and stakeholders, such as suppliers, can lead to the development of new innovations and business opportunities [28]. The two-way communication between infrastructure providers and users can help in identifying the potential areas of investigation. For example, investment in the creation of important infrastructures, such as the Catapult networks and the UK Battery Industrialisation Centre, are the results of such investigations.

Energy is a highly regulated sector, can massively contribute to the economy, and has a fundamental role in carbon emission reduction in the UK economy. Energy RIIs are important for a range of technology readiness levels and stakeholders, including utility companies and the energy supply chain. Additionally, the other economy sectors that energy RIIs contribute to are identified as public policy, transportation, manufacturing, instrumentation, and construction.

Finally, it has been realised that although a majority of infrastructures that focus on R&D are publicly funded, most of the infrastructures that focus on development and deployment are funded by both public and industry funding. Industry will investigate and build infrastructures where these facilities are cost- and use-effective for them. An example is the InTEGReL (Integrated Transport Electricity and Gas Research Laboratory) that the Northern Gas Networks is leading in partnership with Newcastle University and Northern Powergrid. This public–private investment style is necessary when industry is dealing with applied problems that researchers from academia can help to address. Additionally, such infrastructures can help academia to collaborate on real-world challenges, and there are unique opportunities to move forward in science and innovation.

7. Summary

This study was planned to identify the current landscape and future key RIIs for the energy sector in the UK, in order to inform policy makers how to meet the UK Government's 2050 carbon targets. However, the techniques and methods used in this work can be expanded and applied to other countries with access to their internal demonstrators and experts. To achieve our goal and meet our milestones, we completed sets of key detailed stages. Our analysis was developed through a number of activities that enabled us to identify future needs and opportunities, including (i) reviewing current roadmaps and strategy works within sectors and cross cutting areas, (ii) surveys to existing RIIs, in which Survey 1 collected basic information to enable the creation of a map of UK capability and inform judgements on what is in scope, while Survey 2 followed up with RIIs in scope to explore ways of working in more detail, as well as future needs and opportunities, (iii) a user survey, which gave a user perspective on the current landscape and explored future needs and opportunities, (iv) by organising and running a number of workshops/meetings/one-to-one interviews. The diverse stages of this work were reinforced by regular meetings, ongoing consultation, and seeking feedback on draft findings for consultation from the pool of experts.

Our questionnaire approach and analysis have identified 58 energy RIIs which are scattered throughout the UK. These infrastructures work across more than one research sector. For example, energy RIIs have the greatest linkage with environmental and the PS&E sectors. Our data shows the UK's long history in developing energy RIIs with substantial new investment in these capabilities, since 85% of energy RIIs started operation over the last 15 years. We also identified that most of energy RIIs are housed within other organisations which are dependent on long-term funding, such as universities. Finally, it was found that energy RIIs have slightly higher portion of national and international legal entities, and also the highest portion of single-site physical entities, compared to other sectors.

In the next phase of this study, in order to draw the roadmap for the energy system, we identified seven subsectors, as follows: whole energy systems, energy storage, renewable energy sources, carbon capture and storage, fuel cells and hydrogen, alternative fuels, and nuclear energy. We identified challenges and potential RII facilities to address these challenges within each sub-sector.

In conclusion, the key messages of this study are as follows: the first key conclusion is the necessity for further large-scale enterprises, such as the Faraday Institution and NREL (national research laboratories, such as the National Renewable Energy Laboratory) in the USA. The second key conclusion is that the challenges in the energy sector are multidisciplinary and interdisciplinary. To address these challenges, we need large demonstrators of multi-vector energy systems, similar to the InTEGReL, which embeds multi-disciplinary research and innovation, and can raise quality and volume of research. These can learn the needs of several collaborators and participants from government departments and business. The third key conclusion is the need for research into significantly reducing the environmental impacts of technologies used in the energy sector, such as the replacement of rare and costly materials with inexpensive and more abundant ones, mining of materials for low carbon energy technologies, enhanced efficiency of manufacturing processes, and end of life administration or management of technologies used in the energy sector. The fourth key conclusion is the need for enhanced platforms to share data and cyber-physical demonstrators that could be realised by developing an open data platform, improving cyber-physical professionalism, means, and mechanisms, along with big data knowledge. It was believed that these demonstrators could aid the energy division to defeat challenges related to product development, management and operation, as well as challenges related to the reliability and resilience of the energy networks. The fifth conclusion is that energy RIIs are affected by the speed and extent of transformation to a low carbon energy system. Therefore, innovative collaborative projects should increase the competence and capacity of, and connections between, extensive and wide-ranging facilities. Furthermore, it is expected that the UK users who need access to infrastructures will rise across all TRLs and, therefore, we anticipate a systemic change progress across the energy sector.

Author Contributions: Conceptualization, Z.P., S.H.R.H., S.W., D.G. and P.T.; data curation, Z.P. and S.H.R.H.; funding acquisition, S.W., D.G. and P.T.; investigation, Z.P. and S.H.R.H.; methodology, Z.P. and S.H.R.H.; project administration, D.G.; supervision, S.W., D.G. and P.T.; validation, Z.P., S.H.R.H., S.W., D.G. and P.T.; writing—original draft, Z.P. and S.H.R.H.; writing—review & editing, Z.P. and S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Existing Energy Infrastructure

The energy RIIs are classified into the following energy related areas:

- Whole energy systems—interdisciplinary research
- Centre for Renewable Energy Systems Technology (CREST)

The main activity of CREST, as one of the leading international groups working in the field of renewable energy, is to carry out research and education in renewable energy.

- The Tyndall Centre for Climate Change Research

The energy programme of the Tyndall Centre for Climate Change Research includes cultural, political, and institutional factors in addition to technical, economic, and scientific analyses, with an emphasis on international decarbonisation over the next decades.

- Buildings
- Building Research Establishment (BRE)

The BRE is an independent research consultancy with a focus on exploring building techniques and resources, developing buildings through research and testing methods, and creating a more efficient and current built environment.

- Salford Energy House

The main aim is to encourage collaboration between academics, researchers, and industry on energy efficiency within housing. It can help in the testing and demonstration of a broad range of materials, systems, and products.

- Power Systems
- Tony Davies High Voltage Laboratory (TDHVL)

The TDHVL is a centre for research in dielectric materials and insulation systems and high voltage and related phenomena.

- Power Network Demonstration Centre (PNDC)

The PNDC is a combined venture, bringing together academia, government funding agencies, and industry to encourage research and development into business-as-usual status.

- National Grid Power System Research Centre, including the High Voltage and High Current Test Laboratory

The centre has six experimental laboratories, three associated with high voltage engineering, one for dielectric materials, one for protection and control, and one for measurements and instrumentation. As part of the centre, the High Voltage and High Current Test Laboratory provides the opportunity to carry out high voltage testing of equipment used at all voltages of the power system.

- High Power Laser Energy Research facility (HIPER)

HIPER is planned to drive the transition from scientific proof of principle to a demonstration power plant, capable of delivering electricity to the grid.

- Energy system demonstrators
- Integrated Transport Electricity and Gas Research Laboratory (InTEGReL)

The InTEGReL is a partnership between Northern Gas Networks (NGN), Northern Powergrid (NPG), and the Newcastle University-led EPSRC National Centre for Energy Systems Integration (CESI). It will allow energy researchers and engineers to work alongside industrial practitioners for the first time to explore the transformative benefits of coupled gas, electricity, and heat systems, and to carry out full-scale cross-vector demonstrations of novel approaches to integrated energy systems.

- Keele Smart Energy Network Demonstrator (SEND)

The SEND is a living laboratory 'at scale' for research and development and the testing of new energy efficient technologies in a real-world environment. It encourages collaboration between industry and academia for development of energy technologies in several fields including security of energy supply, carbon reduction, network demand side management, and energy generation performance monitoring.

- Nuclear
- Culham Centre for Fusion Energy (CCFE), including the Joint European Torus (JET) and the Mega Amp Spherical Tokamak (MAST)

The CCFE is interested in many issues that are common to both fission and fusion activities. The CCFE is host to the UK domestic fusion programme, the Mega Amp Spherical Tokomak (MAST) and the Joint European Torus (JET). The JET, which is located at the CCFE and primarily funded through the EU Framework Programme, is the main EU fusion experiment. The MAST is a UK research machine located at the CCFE.

- ORION

ORION, as part of the Atomic Weapons Establishment (AWE), is a laser facility to study high energy density physics, and is suitable for ICF studies.

- National Nuclear User Facility (NNUF), including the Microscope and Ion Accelerator for Materials Investigations facility (MIAMI)

The NNUF is a distributed facility and is intended to provide the necessary supporting equipment for the preparation, transport, and study of highly active materials. The MIAMI is a custom-designed facility, which uses ion beams to simulate the effects of radiation damage in-situ and allows for nanoscale examination.

- Dalton Cumbria Facility (DCF) of Manchester University

The DCF is a core component of the NNUF, and is designed to complement and significantly expand the nuclear research and education capability of the UK's nuclear R&D sector.

- Nuclear Advanced Manufacturing Research Centre (AMRC)

The AMRC supports industry with manufacturing issues and aims to help businesses become suppliers of choice to the global civil nuclear industry.

- National Nuclear Laboratory

The NNL is the largest nuclear laboratory in the UK, which was set up to develop and applying techniques to decommission nuclear facilities, including wastes management and decommissioning projects, environmental and effluent management, measurement and analysis, and waste immobilisation technology.

- CCS
- Peterhead Carbon Capture and Storage (CCS) Project

It is the world's first gas-fired power station to host a full-chain carbon capture and storage (CCS) project on a commercial scale. The plant will power approximately half a million homes with clean electricity. It will capture approximately one million tonnes of carbon dioxide (CO_2) a year from the power station's flue gas, and transport and permanently store it in a depleted gas reservoir under the North Sea.

- Renewable Energy Sources
- Wind
- National Renewable Energy Centre (NAREC)

The NAREC is an independent centre for the development, testing, and commercialisation of next generation technologies for the global wind energy industry.

- Energy Technology Centre (ETC)

The ETC is a specialist in full system technology testing, as well as in turbine component testing. They are able to assess how innovations respond to wind, thermal systems, and the marine environment.

- Hunterston Offshore Wind Turbine Test facility

The facilities, once complete, will be able to test up to three wind turbine prototypes of offshore wind turbines.

- Marine, wave and tidal
- European Marine Energy Centre (EMEC)

The centre is intended to supply innovators with a means to test technologies with a focus on producing electricity through the influence of wave and tidal stream environments.

- Marine renewables test centre

The centre, once complete, will be used for the development, design, and testing of marine renewable construction materials and prototype foundations.

- Peninsular Research Institute for Marine Renewable Energy (PRIMaRE)

The PRIMaRE is a network of world-class research institutions with facilities being capable of the scale testing of devices and, additionally, the study of seabed device interactions.

- FloWave Ocean Energy Research Facility

The FloWave facility is a cutting-edge academic research facility for wave and tidal current interactions. It is capable of testing devices and arrays in multiple current and wave regimes that effectively replicate ocean conditions found around the UK.

- Offshore Renewable Energy Catapult (ORE Catapult), National Renewable Energy Centre

The ORE Catapult is a research centre with a focus on evolving grid integration of renewable energy systems and coordinating the growth and distribution of offshore wind, wave, and tidal energy generation technology.

- Wave Hub Ltd.

The Wave Hub facility is a marine renewable energy test facility, which has grid connected infrastructure and the capability to host offshore wind turbine foundations. The aim of the hub is to aid in the advancement of wave technologies and innovation and research in this field.

- Solar
- NaREC Photovoltaic Technology Centre (PVTC)

The PVTC is a test facility well-equipped with a solar cell process line and characterisation laboratory, and is dedicated to providing testing and development services to the energy sector.

- Centre for Solar Energy Research (CSER)

The CSER has proven expertise and a world-class reputation in researching novel photovoltaic materials and devices.

- Low Carbon Research Institute (LCRI)

The multidisciplinary LCRI aims to support the energy sector, in the UK and globally, to develop low carbon generation, storage, distribution, and end use technologies, and to offer policy advice to help deliver a low carbon future.

- Alternative Fuels
- European Bioenergy Research Institute (EBRI)

The EBRI acts as a focus for work on biomass conversion and the utilisation of products for renewable power, heat, transport fuels, hydrogen, and chemicals. The EBRI offers feedstock, power, and equipment tests, and boasts biomass processing and analysis and heterogeneous catalysis capabilities. It is able to offer a full cycle of testing, from analytical scale research through to semi-industrial demonstrator level testing.

- Hydrogen
- Renewable Hydrogen Research and Development Centre

A centre on electrolytic hydrogen production, compression and storage, which benefits from photovoltaic solar arrays, PEM fuel cells, and hydrogen vehicle refuelling.

- Energy technologies & markets
- The Energy Centre Thornton Science Park

The centre provides collaboration between academia and industry to develop and demonstrate new intelligent energy technologies for the energy market.

References

1. Stark, C.; Thompson, M. *Net Zero The UK's Contribution to Stopping Global Warming*; Committee on Climate Change: London, UK, 2019.
2. *The UK's Research and Innovation Infrastructure: Landscape Analysis*; UK Research and Innovation (UKRI): Swindon, UK, 2020.
3. *Industrial Strategy: Building a Britain Fit for the Future*; Department for Business, Energy and Industrial Strategy: London, UK, 2017.
4. Hartley, P.R.; Medlock, K.B. The valley of death for new energy technologies. *Energy J.* **2017**, *38*, 33–61. [CrossRef]
5. Hirzel, S.; Hettesheimer, T.; Viebahn, P.; Fischedick, M. Bridging the valley of death: A multi-staged multi-criteria decision support system for evaluating proposals for large-scale energy demonstration projects as public funding opportunities. In Proceedings of the ECEEE Industrial Summer Study, Berlin, Germany, 11–13 June 2018.
6. Nemet, G.F.; Zipperer, V.; Kraus, M. The valley of death, the technology pork barrel, and public support for large demonstration projects. *Energy Policy* **2018**, *119*, 154–167. [CrossRef]
7. Mossberg, J.; Söderholm, P.; Hellsmark, H.; Nordqvist, S. Crossing the biorefinery valley of death? Actor roles and networks in overcoming barriers to a sustainability transition. *Environ. Innov. Soc. Transit.* **2018**, *27*, 83–101. [CrossRef]

8. Upadhyayula, V.K.; Gadhamshetty, V.; Shanmugam, K.; Souihi, N.; Tysklind, M. Advancing game changing academic research concepts to commercialization: A Life Cycle Assessment (LCA) based sustainability framework for making informed decisions in Technology Valley of Death (TVD). *Resour. Conserv. Recycl.* **2018**, *133*, 404–416. [CrossRef]
9. Hosseini, S.H.R.; Allahham, A.; Taylor, P. Techno-economic-environmental analysis of integrated operation of gas and electricity networks. In Proceedings of the 2018 IEEE International Symposium on Circuits and Systems (ISCAS), Florence, Italy, 27–30 May 2018; pp. 1–5.
10. Hosseini, S.H.R.; Allahham, A.; Vahidinasab, V.; Walker, S.L.; Taylor, P. Techno-economic-environmental evaluation framework for integrated gas and electricity distribution networks considering impact of different storage configurations. *Int. J. Electr. Power Energy Syst.* **2021**, *125*, 106481. [CrossRef]
11. Hosseini, S.H.R.; Allahham, A.; Walker, S.L.; Taylor, P. Optimal planning and operation of multi-vector energy networks: A systematic review. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110216. [CrossRef]
12. Skea, J.; Hannon, M.; Rhodes, A. *Investing in a Brighter Energy Future: Energy Research and Training Prospectus*; Imperial College: London, UK, 2013.
13. *A Review of the Civil Nuclear R&D Landscape in the UK*; UK HM Government: London, UK, 2013.
14. *A guide to Energy Sector Testing & DemonstrationFacilities*; Energy System Catapult: Birmingham, UK, 2019.
15. Bateman, N. *A Report on the Scale and Scope of Academic Energy research in the UK 2015*; EPSRC: Swindon, UK, 2015.
16. *UKRI Infrastructure Roadmap, Initial Analysis of Infrastructure Questionnaire Responses And Description of the Landscape*; UK Research and Innovation (UKRI): Swindon, UK, 2019.
17. Mission Innovation Secretariat, Mission Innovation: Accelerating the Clean Energy Revolution Strategies, Progress, Plans and Funding Information. 2017 March 2020. Available online: https://iea-etsap.org/workshop/stuttgart_nov2018/20181109_MI%20Tracking_ETSAP%20workshop.pdf (accessed on 18 March 2022).
18. Pourmirza, Z.; Brooke, J.M. A Realistic ICT Network Design and Implementation in the Neighbourhood Area of the Smart Grid. *Smart Grid Renew. Energy* **2013**, *4*, 436–448. [CrossRef]
19. Pourmirza, Z.; Walker, S.; Brooke, J. Data reduction algorithm for correlated data in the smart grid. *IET Smart Grid* **2021**, *4*, 474–488. [CrossRef]
20. Ebrahimy, R.; Pourmirza, Z. Cyber-interdependency in Smart Energy Systems. In Proceedings of the 3rd International Conference on Information Systems Security and Privacy (ICISSP 2017), Porto, Portugal, 19–21 February 2017; SCITEPRESS–Science and Technology Publications: Hampshire, UK, 2017.
21. Pazhoohesh, M.; Pourmirza, Z.; Walker, S. A comparison of methods for missing data treatment in building sensor data. In Proceedings of the 2019 IEEE 7th International Conference on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 12–14 August 2019.
22. Cameron, C.; Patsios, C.; Taylor, P.C.; Pourmirza, Z. Using self-organizing architectures to mitigate the impacts of denial-of-service attacks on voltage control schemes. *IEEE Trans. Smart Grid* **2018**, *10*, 3010–3019. [CrossRef]
23. Pourmirza, Z.; Srivastava, A. Cybersecurity Analysis for the Communication Protocol in Smart Grids. In Proceedings of the 2020 IEEE 8th International Conference on Smart Energy Grid Engineering (SEGE), Oshawa, ON, Canada, 12–14 August 2020.
24. Khalil, M.; McGough, S.; Pourmirza, Z.; Pazhoohesh, M.; Walker, S. (2021, April). Transfer Learning Approach for Occupancy Prediction in Smart Buildings. In Proceedings of the 2021 12th International Renewable Engineering Conference (IREC), Amman, Jordan, 14–15 April 2021; pp. 1–6.
25. O'Dwyer, E.; Pan, I.; Charlesworth, R.; Butler, S.; Shah, N. Integration of an energy management tool and digital twin for coordination and control of multi-vector smart energy systems. *Sustain. Cities Soc.* **2020**, *62*, 102412. [CrossRef]
26. Britton, J.; Minas, A.M.; Marques, A.C.; Pourmirza, Z. Exploring the potential of heat as a service in decarbonization: Evidence needs and research gaps. *Energy Sources Part B Econ. Plan. Policy* **2021**, *16*, 999–1015. [CrossRef]
27. Pumphrey, K.; Walker, S.L.; Andoni, M.; Robu, V. Green hope or red herring? Examining consumer perceptions of peer-to-peer energy trading in the United Kingdom. *Energy Res. Soc. Sci.* **2020**, *68*, 101603. [CrossRef]
28. *The UK's Research and Innovation Infrastructure: Opportunities to Grow Our Capability*; UK Research and Innovation (UKRI): Swindon, UK, 2019.