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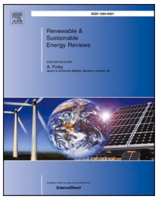

Future pathways for energy networks: A review of international experiences in high income countries

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ABSTRACT

Energy networks are the systems of pipes and wires by which different energy vectors are transported from where they are produced to where they are needed. As such, these networks are central to facilitating countries' moves away from a reliance on fossil fuels to a system based around the efficient use of renewable and other low carbon forms of energy. In this review we highlight the challenges facing energy networks from this transition in a sample of key high income countries. We identify the technical and other innovations being implemented to meet these challenges and describe some of the new policy and regulatory developments that are incentivising the required changes. We then review evidence from the literature about the benefits of moving to a more integrated approach based on the concept of a Multi-Vector Energy Network (MVEN). Under this approach the different networks are planned and operated together to achieve greater functionality and performance than simply the sum of the individual networks. We find that most studies identify a range of benefits from an MVEN approach, but that these findings are based on model simulations. Further work is therefore needed to verify whether the benefits can be realised in practice and to identify how any risks can be mitigated.

1. Introduction

The 2015 Paris Agreement on climate change is having profound implications on the way that energy is generated, distributed and used across the world [1]. Energy networks are at the heart of many energy systems, connecting suppliers and users of energy by exploiting and facilitating temporal and spatial diversity in energy production and use, and leveraging economies of scale where they exist. Energy network infrastructure, operation and management, and regulation are likely to experience significant changes in many countries as the challenges of decarbonisation intersect with the need to maintain energy security and affordability. Notably the change from fossil fuel based energy systems to systems that incorporate an increasing share of renewable energy (RE) and other new energy vectors (e.g. hydrogen) will increase the need for flexibility, including through greater interconnectedness between networks and new forms of energy storage [2,3]. A further challenge for many countries in the global south is to provide their growing populations with access to modern forms of energy that can provide lighting, cooking and other energy services in a clean and affordable way [4]. Again energy networks, particularly for electricity, are central to the success of such ambitions and include the development of micro-grids through to major grid-extension projects [5].

Given the very different situations of countries around the world and the wide range of network configurations that might be appropriate for different energy vectors, it is not possible to do justice to the whole topic in a single article. This review therefore focuses on the situation in high income countries that belong to the Organisation of Economic Co-operation and Development. In these countries, energy networks face many shared challenges, such as those around RE integration, and are active fields for research [6]. In countries where electricity generation is being decarbonised, the substitution of fossil fuels by electricity to reduce emissions from end-use sectors, such as buildings and transport is also receiving considerable attention [7]. Decarbonising heat is a particular challenge in some countries. For instance, in the UK and Netherlands, over 85% of domestic heating is supplied by natural gas because of the extensive transmission network. As a result, there has been very slow deployment of District Heating (DH), heat pumps and other low carbon heating options [8,9]. In these countries, the debate around repurposing the natural gas network to carry hydrogen and other low-carbon gases (e.g., biomethane) is gathering momentum. Depending on the method of production, these gases could offer a potential route to low-carbon energy use in both buildings and industry. In contrast, the context is quite different in Finland, Denmark, Germany,

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Abbreviations

CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heating and Power
CPUC	California Public Utilities Commission
DH	District Heating
DHC	District Heating and Cooling
DNO	Distribution Network Operator
DSO	Distribution System Operator
EECA	Energy Efficiency and Conservation Authority
E2T	Electricity –to-Thermal
IES	Integrated Energy System
IRM	Innovation Roll-out Mechanism
MVEN	Multi-Vector Energy Network
NIA	Network Innovation Allowance
NIC	National Infrastructure Commission
P2G	Power-to-Gas
P2H	Power-to-Hydrogen
R&D	Research and Development
RDF	Refuse Derived Fuel
RE	Renewable Energy
SNG	Synthetic Natural Gas
TSO	Transmission System Operator
UAE	United Arab Emirates
V2G	Vehicle-to-Grid
VRE	Variable Renewable Energy

Belgium, Korea and Japan where there are already significant contributions from alternative heating systems [10–12].

The implications of moving to greater electrification of road transport is another area of significant interest, with the impact on networks remaining uncertain. Greater electricity use has the potential to cause a burden, in terms of requiring the reinforcement of local electricity grids, but could also deliver benefits to network operation from vehicle-to-grid technology that might help provide enhanced flexibility at a local level [13–17].

Given the potential for extensive changes in the energy vectors being used in the future, there is growing interest in the benefits to energy networks of a more holistic approach. This would seek to harness the benefits of planning and operating networks together, rather than separately as is often the case now [18]. As a result, research is being undertaken to understand if, and how, Multi-Vector Energy Network (MVEN) and Integrated Energy System (IES) approaches can solve common network challenges relating to security, reliability, and flexibility. Facilitating the development of multi-energy technologies and enhancing interdependencies and interactions among electricity, gas and other energy networks could help minimise system costs and maximise environmental performance [19]. Therefore MVENs have been suggested as an approach to deal with the challenges of meeting Net Zero climate targets [20].

Increasingly, questions are being explored around the fuels that will play a significant future role and the modifications to network systems that will be needed, plus the willingness of consumers to accept such changes. Thus studies investigating potential future energy pathways for various countries are increasing [21–23]. However, there are relatively few comparative studies that focus on the network implications of these future pathways across multiple countries. In the energy system transitions literature, making comparisons across different jurisdictions is a familiar approach to enhance learning about the interactions between society, technologies, policies, and related programmes [24]. Therefore, this paper aims to review international experiences with energy networks to improve our understanding of the drivers for the transitions currently underway, the solutions being proposed, and the challenges being faced. The intention is to provide beneficial insights to researchers, industry players, regulators, and policymakers.

Specifically, this paper attempts to answer the following questions:

Q1. How are energy networks operated internationally regarding ownership, governance and regulation and how is this changing?

Q2. What are the major challenges facing energy networks and how do these vary between countries?

Q3. How are energy networks in different countries innovating in response to these challenges and what policy frameworks are supporting the required changes?

Q4. To what extent is an MVEN approach evidenced internationally and what benefits and challenges are expected if the approach is adopted?

The rest of the paper is structured as follows: section 2 explains the review methodology, while section 3 presents the challenges facing energy networks and how they are responding. The evidence regarding MVENs is then reviewed in section 4; followed by conclusions in section 5.

2. Material and methods

We use a purposive sampling technique to identify a range of advanced economies from which evidence is gathered and reviewed. First, we undertook a scoping review of energy networks developments in twelve countries with a wide geographical distribution. In the second stage, we identified eight countries for detailed investigation, as shown in Table 1, based on whether they exhibited the following attributes (scores in brackets).

- Evidence of two or more energy networks (5)
- Evidence of MVEN or IES (5)
- Evidence of significant RE in networks (10)
- Evidence of network challenges and solutions (10)
- Evidence of a deliberate policy to increase low carbon energy (10)

This study uses Critical Case Sampling to identify countries of interest, which is a non-probabilistic approach similar to purposive sampling [25]. This method produces a small sample that highlights vital information relevant to the aims and objectives of the research. Participants or samples are selected based on their richness and relevance of information to help answer specified research questions [26]. Patton [27] suggests that information-rich cases are those that offer insights about, and deep understanding of, issues concerning the intended inquiry. The advantages and disadvantages of purposive sampling have been discussed by Sharma [28]. It has the potential for introducing bias, but this can be addressed if certain criteria are developed from a framework and used for sampling, as is the case here.

To ensure that our investigation of the eight selected countries was as comprehensive as possible we drew on the co-evolutionary framework for energy system transitions developed by Foxon [29]. This framework identifies five dimensions – ecosystems (e.g. living systems in nature), technologies, institutions (e.g. laws and regulations), business strategies and user practices (e.g. patterns of human behaviour) – which coevolve, through mutual causal influences, to shape alternative transition pathways (Fig. 1).

Using this approach, both grey and peer-reviewed literature were collected and reviewed covering all the topics identified by the framework. The review steps included:

Table 1
Critical factors for sampling countries for study.

Country	With two or more energy networks	Evidence of MVEN or IES	Significant share of wind and solar in the electricity produced	Evidence of networks challenges and solutions	Deliberate policy on low carbon energy	Total score	Selected cases
Germany	10	5	10	5	10	40	✓
Denmark	10	5	10	5	10	40	✓
Netherlands	10	5	10	5	10	40	✓
France	10	5	0	5	10	30	
Italy	10	5	0	5	10	30	
Sweden	10	5	10	5	10	40	✓
New Zealand	10	5	10	5	10	40	✓
California (USA)	10	5	10	5	10	40	✓
Canada	10	5	0	5	10	30	
Japan	10	5	10	5	10	40	✓
South Korea	10	5	0	5	10	30	
United Kingdom	10	5	10	5	10	40	✓

Germany, Denmark, Netherlands, Sweden, New Zealand, USA (State of California), Japan and United Kingdom were selected as cases.

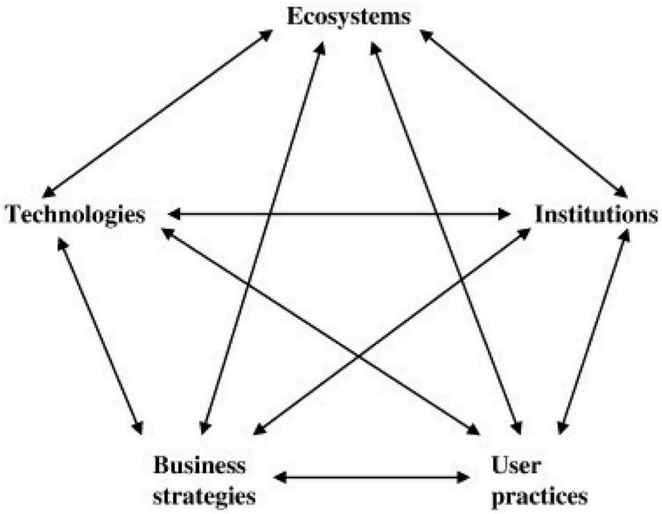

Fig. 1. A coevolutionary framework is used to identify the elements considered in the review (Source [29]: [11]).

- Executing country-specific searches on networks of various energy vectors with regards to the chosen themes. One set of results related to reports from utilities, regulators, energy consultancies, sector ministries and agencies, while the other set was peer reviewed papers from various databases.
- Summarising the literature under the themes of the investigation.
- Analysing the results to identify similarities, differences, and distinctiveness.

3. International experience on energy networks transitions

This section starts by briefly presenting the energy policy context in each of the eight countries chosen for the review. It then discusses the ownership, regulation, and operation of energy networks, the challenges that these networks are increasingly facing and how they are responding. The aim is to delineate the similarities and differences between the countries and, importantly, to draw lessons that could be relevant to a range of countries. Many energy networks are having to evolve as they respond to policy priorities and regulations that are driven by countries' climate change strategies, while also taking account of country-specific issues such as geography and the type of energy resources available. In some countries, there have been significant changes to network operations over the last ten years, with deliberate policies to drive innovation and investments into low carbon networks. While in other countries the changes have been less significant so far.

3.1. Energy policy context

The countries in our review all aim to have energy policies that find an appropriate balance between security, affordability and sustainability in how energy is supplied and used [30,31]. Addressing climate change has been a growing energy policy priority over the last 30 years. All the countries sampled now have targets to reach net-zero greenhouse gas emissions by the middle of the century, with an increasing share of renewable energy being a key strategy (Table 2).

The last year has seen many countries augment these targets with significant new policies that will impact energy networks. For instance the European Union (with members including Denmark, Germany, the Netherlands and Sweden) has recently brought forward proposals for a European Green Deal [38], which includes the goals of building interconnected energy systems and better integrated grids to support renewable energy sources, decarbonising the gas sector and developing the potential of Europe's offshore wind sector. The UK has its own commitments outlined in The Ten Point Plan for a Green Industrial Revolution [39] which aims to advance offshore wind and drive the growth of low carbon hydrogen. In the US, the Infrastructure Investment and Jobs Act [40] includes significant investment in the electricity grid to prevent outages and enhance its resilience, as well as increasing funding for clean hydrogen programmes. In Japan the Sixth Strategic Energy Plan [34] will increase the contribution of electricity from renewable sources, while also using hydrogen to help decarbonise end-use sectors such as transport and industry. Similarly, New Zealand's efforts to tackle climate change involve accelerating the deployment of renewable energy and developing green hydrogen [41].

Table 2
Targets for Net-Zero GHG emissions and renewable energy.

	Year for Net Zero GHG emissions	Renewable energy targets (2030 unless stated)
California	2050[a]	60% of electricity
Denmark	2050	55% of all energy
Germany	2045	30% of all energy
Japan	2050	36–38% of electricity
Netherlands	2050	27% of all energy
New Zealand	2050	90% of electricity by 2025
Sweden	2045	65% of all energy[b]
United Kingdom	2050	50 GW of offshore wind

[a] Target is for the United States. California has a GHG reduction target of 40% below 1990 levels by 2040.

[b] Not a formal target, but based on official projections.

Sources [32–37]:

However, the recent gas and oil price rises, knock-on impacts on electricity costs, plus the war in Ukraine, have reminded countries, particularly in Europe, that energy security and affordability cannot be ignored as countries transition to lower carbon energy systems. While some Governments and parts of industry have argued that the response should be to increase oil and gas production [42], other countries see it as an opportunity to accelerate the green transition and to reduce dependence on fossil fuels [43]. There are also growing concern about the impact of high oil and gas prices on consumers [44].

3.2. Ownership, governance and regulation of energy networks

The last 30 years have seen increasing involvement of the private sector in owning and operating energy networks [45](Table 3). This has been driven by a political determination in many countries to liberalise and unbundle the energy sector to increase competition and efficiency [46]. However, significant differences can still be observed between countries. For instance, energy networks in the UK are nearly all privately owned, whereas Denmark, Netherlands and Japan have both private and public ownership. Germany, after privatising in 2001, have started municipalising ownership and operations of their networks. At the transmission level, the network is privately owned with indirect public ownership, while at the distribution level the networks are predominantly publicly and privately owned. Sweden has a combination of public, private and municipal ownership, and some foreign ownership. New Zealand and California are very similar in their ownership structure with no private ownership but rather networks are state and/or local publicly owned. Before 1980, California Utilities supplied virtually all the services to its customers. However, this has increasingly changed with other services including gas production, storage and even supply being liberalised. California's regulated utilities do not own any natural gas production facilities, and the California Public Utilities Commission does not regulate California gas producers [47].

Most of the countries reviewed have completely unbundled their power and gas sectors, except for Japan which has partially unbundled. Japan had up to 2020 to pursue a total separation of its distribution and transmission sectors with a total liberalised retail sector in order to increase competition and transparency [48].

Regulation of gas and electricity networks (which are natural monopolies) is used to protect consumers from being unfairly exploited by network operators by ensuring adequate investment, while controlling prices with appropriate incentives [49,50]. Regulatory frameworks tend to evolve over time as the sector adapts to meet new challenges. This is best demonstrated in the power sector, which is changing technologically, but also in the associated spheres of policy, finance, markets and institutions [51,52].

The countries sampled show a number of similarities regarding regulatory and governance structures, with either a cost-plus or price/revenue cap regulatory regime generally being implemented (Table 3). Conventionally, these instruments are a mechanism to incentivise cost efficiency in network operations by preventing excessive costs being passed through to consumers in a prescribed regulatory period [53]. They comprise the regulatory decision process, regulatory period, allowed expenditures, assessment of a regulatory asset base, and determination of a rate of return, and treatment of OPEX and CAPEX with a predetermined efficiency target. To incentivise efficiency, networks that meet targets are rewarded with an increased cap; whereas those that fail to achieve their targets suffer a reduced cap [54].

It appears almost all of the European Union countries in our sample use the Price/Revenue Cap regulation with an incentive for efficiency and innovation. The Council of European Energy Regulators [54] observed that many European regulatory systems use similar instruments or a combination of instruments and so no system is completely unique. Thus, for example, the incentive regulation ordinance (Price/Revenue Cap) of 2007 in Germany is comparable with the UK's RPI-X regime (now replaced with the RIIO formula) while the Netherlands and Sweden have similar practices in setting tariff regulation regimes.

Nonetheless, while the objective underscoring the various regulatory regimes is similar, some differences exist [53]. For example, the shares of total network costs due transmission and distribution activities vary significantly across countries, even within the European Union. This infuses some diversity in terms of national practices regarding network tariff regulation and cost allocation [55]. For instance, there are variations relating to how assets may be depreciated and valued, and the length of the regulatory period [54,56,57].

All the countries in our sample have industry codes or guidelines within which the electricity and gas markets operate, and these must be complied with by licensees. They cover network codes, market regulation, technical regulations, tender conditions and requirements for ancillary services, as well as trade-rules across borders [58]. In Germany, Sweden, Denmark and Netherlands, system operators are the custodians of the codes with approval from the regulators and subject to European regulations for operations, markets and grid access [59,60]. In New Zealand, the electricity authority and a range of contracted service providers develop, administer and enforce the codes for the electricity networks [61].

Unlike gas and electricity, District Heating and Cooling (DHC) networks are only "lightly" regulated in some of the countries reviewed. For example, some ex-post regulation at the user end in Denmark, Sweden, Netherlands and Germany. Even in these cases, regulation is directed at retail markets rather than at the distribution networks. This has been highlighted as a challenge to promoting DHC, as a lack of economic regulation risks the possibility of passing cost inefficiencies onto consumers [62]. There is a huge potential for DH in New Zealand via direct heat utilisation from geothermal sources and solar heating, but this has not yet been exploited to any extent [41,63]. There is evidence that policy reforms are favouring DH networks in many of the countries reviewed, but there are challenges regarding competition with natural gas and other fuels as in the case of the UK and Netherlands. Regarding ownership, most of the countries have public and municipal ownership, even though recent liberalisation is promoting private and mixed ownership archetypes [see appendix]. Thus, ownership is becoming more diverse to increase competition in the DHC industry. Unlike for gas and electricity, competition at the wholesale level is unusual in DHC because the market is typically highly integrated. Thus, to protect consumers, an overseeing agency usually applies technical codes and pricing guidelines to the vertically integrated system or the distribution system [64]. To increase competition, there are different Third Party Access (TPA) models that are applied to DH in Germany, Sweden, and Netherlands [65].

3.3. Network operation and challenges

3.3.1. Integrating renewable energy

The transition to low carbon energy systems, incorporating increasing quantities of RE, is driving changes to network planning, investments, and operations in many countries. This increased investment in RE is a result both of declining costs of a number of RE technologies and deliberate energy policies to encourage their use. For instance, in the electricity sector, high targets for RE shares are evident in a number of countries: 80% of electricity by 2050 for Germany, 50% by 2035 for Denmark [60] and 60% by 2030 for California [37]. Meeting these targets will require both advances in technological aspects of networks, and changes to network operations, management, market designs, codes and regulatory frameworks [66,67].

A particular challenge facing electricity networks is to integrate large shares of Variable Renewable Energy (VRE) such as solar and wind [68,69]. Examples of the challenges facing countries can be seen in

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Table 3
Summary of market structures and regulatory frameworks in case study countries.

Germany		Market Structure and Regulation			
		Gas TSO	Gas DSO	Electricity TSO	Electricity DSO
Market Structure	Number of Operators	16	700	4	850
	Ownership	Mainly Private Investors, Indirect Public Ownership	Private and Local public ownership	Mainly Private Investors, Indirect Public Ownership	Private and Local public ownership
Regulatory Framework	Authority	Bundesnetzagentur	Bundesnetzagentur and other federal state authorities	Bundesnetzagentur	Bundesnetzagentur and other federal state authorities
	Reg. System	Incentive Regulation/Revenue Cap			
	Legal Framework	EnWG, ARegV, GasNEV		EnWG, ARegV, StromNEV	
Denmark		**Gas TSO**	**Gas DSO**	**Electricity TSO**	**Electricity DSO**
Market Structure	Network Operators	1	3	1	47
	Ownership	Independent public enterprise owned by Government	Public ownership	Independent public enterprise owned by Government	Private and Local public ownership
Regulatory Framework	Authority	Danish Utility Regulator (DUR)	Danish Utility Regulator (DUR)	Danish Utility Regulator (DUR)	Danish Utility Regulator (DUR)
	Reg. System	Strict Cost Plus	Revenue Cap	Strict Cost Plus	Revenue Cap
	Legal Framework	The Natural Gas Supply Act	The Natural Gas Supply Act	The Electricity Supply Act	The Electricity Supply Act
Sweden		**Gas TSO**	**Gas DSO**	**Electricity TSO**	**Electricity DSO**
Market Structure	Network Operators	1	6	2	184
	Ownership	Foreign Ownership	Municipality and Foreign Ownership	State Owned and Private	State, Municipality, Private, and foreign ownership
Regulatory Framework	Authority	Swedish energy markets inspectorate, Ei			
	Reg. System	Revenue Cap			
	Legal Framework	Naturgaslagen (Gas Act)		Ellagen (Electricity Act)	
Netherlands		**Gas TSO**	**Gas DSO**	**Electricity TSO**	**Electricity DSO**
Market Structure	Network Operators	1 (GTS)	8	1 (TenneT)	7
	Ownership	State Owned	Local Public Owned	State Owned	Local Public Owned
Regulatory Framework	Authority	Authority for Consumers and Markets (ACM)	ACM	ACM	ACM
	Reg. System	Incentive Regulation/Revenue Cap	Incentive Regulation/Price Cap	Incentive Regulation/Revenue Cap	Incentive Regulation/Price Cap
	Legal Framework	Gaswet (Gas Act)		Electriciteitswet 1998 (Electricity Act)	
Japan		**Gas TSO**	**Gas DSO**	**Electricity TSO**	**Electricity DSO**
Market Structure	Network Operators	198		10	
	Ownership	Public Ownership (25)	Private Ownership (173)	Private Owned	
Regulatory Framework	Authority	Ministry of Economy, Trade, and Industry (METI)			
	Reg. System	Cost-Plus			
	Legal Framework	Gas Business Act (1954)		Electricity Business Act in 2014	
California (USA)		**Gas TSO**	**Gas DSO**	**Electricity TSO**	**Electricity DSO**
Market Structure	Network Operators	6	7	6	
	Ownership	State Owned	Local Public Owned	State Owned	Local Public Owned
Regulatory Framework	Authority	California Public Utilities Commission (CPUC) Federal Energy Regulation Commission (FERC)		California Public Utilities Commission (CPUC) Federal Energy Regulation Commission (FERC)	
	Reg. System	Cost-Plus (Predetermined- RoR)		Cost-Plus (Predetermined- RoR)	
	Legal Framework				
New Zealand		**Gas TSO**	**Gas DSO**	**Electricity TSO**	**Electricity DSO**
Market Structure	Network Operators	1 (FirstGas)	4	1 (Transpower)	29
	Ownership	State Owned	Local Public Owned	State Owned	Local Public Owned
Regulatory Framework	Authority	Gas Industry Company Limited (GIC)	ACM	Electricity Authority (EA) Commerce Commission (CC) Energy Efficiency and Conservation Authority (EECA)	
	Reg. System	Price-quality control regime/Price-Cap 4 years		Price-quality control regime/Price-Cap 5 years	
		Gas Act 1992		Part 4 of the Commerce Act 1986	

(*continued on next page*)

Table 3 (*continued*)

Germany		Market Structure and Regulation			
		Gas TSO	Gas DSO	Electricity TSO	Electricity DSO
	Legal Framework	Government Policy Statement on Gas Governance 2008 Part 4 of the Commerce Act 1986			
United Kingdom		**Gas TSO**	**Gas DSO**	**Electricity TSO**	**Electricity DSO**
Market Structure	Network Operators	1	8	3	14
	Ownership	Private	Private	Private	Private
Regulatory Framework	Authority	GEMA -Ofgem			
	Reg. System	Revenue = Incentive + Innovation + Output (RIIO2 -Gas)		Revenue = Incentive + Innovation + Output (RIIO2 -Electricity)	
	Legal Framework	Gas Act 2000 Utilities Act 2000 Energy Act 2004, 2008, 2010, 2011		Electricity Act 2000 Utilities Act 2000 Energy Act 2004, 2008, 2010, 2011	

California and Denmark. In California grid integration and balancing [51] is exemplified by the so-called “duck-curve” (which refers to the timing imbalance between peak demand and RE production) and in Denmark uncertainty in wind power output can lead to imbalances between electricity generation and consumption [70].

There are also network constraints in both high voltage and low voltage systems that hinder integration of more VRE in the UK, USA and Germany [71–74]. This network challenge hampers reliable operations and control [75] and will require both increased flexibility in the system and strengthened networks that are better able to connect the geographical distribution of renewables to where power is demanded. Transforming the planning and operation of transmission and distribution systems to enhance grid integration and flexibility remains a vital challenge to energy networks [68,76]. A number of international organisations [77] suggest that successfully integrating high shares of VRE requires a three-level approach that holistically considers technical, institutional, and economic elements. Therefore innovation ought to increase the technical capabilities of networks to increase flexibility, transform the roles and responsibility of relevant actors, as well as revise the system operation and market rules [6,54].

3.3.2. *Greater electrification*

Many studies have highlighted the need to increase substantially the electrification of energy provision, in order to reduce greenhouse gases by increasing renewable electricity consumption [78,79]. The need for greater electrification in homes, transport and industries can bring both environmental and economic benefits to the end-user [80]. However, such a transition could pose challenges to the operations and management of energy networks [21]. Such steps will require that transmission and distribution networks are upgraded and reinforced, and these come with their own technological and economic issues. For example in the UK, security of supply, balancing and network resilience are some of the challenges expected from increased electrification [81,82]. Almost all the countries studied are considering this option, which makes increased electrification a common intervention in the energy transition. However, different approaches with various degrees of electrification efforts at either the supply-side and/or the demand-side are evident. For example, California, Denmark, Netherlands, Sweden and the UK all have plans to ban within the next 15 years the sale of cars and/or other light vehicles that run exclusively on fossil-fuels [83]. There are also proposals to stop the use of natural gas in new buildings in parts of California [84] and to stop gas boilers being installed in new homes in the UK [85]. In contrast, Japan is aiming for greater electrification as part of its long-term energy plans, but has yet to introduce concrete policies [86]. Countries considering the increased use of electricity to meet seasonal heating needs, such as the UK, USA, Germany and Sweden could experience very high peak demands on the transmission and distribution networks in severe winters. This could be further exacerbated by the roll-out of electric vehicles depending on their charging and use patterns and/or the responsiveness of other demand management tools [87].

3.3.3. *Dealing with uncertainty*

Energy networks in many countries are facing uncertainties regarding political priorities for the energy system, the overarching policy landscape, the future direction of technology development and the detailed regulatory environment in which they operate. These are adding to the operational challenges and increasing the risks and the required investments needed for innovation solutions to balance the trilemma of security, affordability and environmental protection [88–91].

These uncertainties are exemplified by the UK, which is usually regarded as having a stable investment climate, with potentially far reaching political discourses on renationalisation and interventions on energy prices [92,93]. The UK National Grid and the Energy Network Association have highlighted that such political risks could act as an impediment to dealing with the challenges facing energy networks, as they may increase the costs of financing the necessary investments [94].

Alternative pathways to decarbonise the energy system are being considered in various countries and these could change the demand and supply of particular energy vectors, with consequent implications for the networks that transport them [95]. For example, some countries are considering increasing electric vehicles usage, heat pumps and electric boilers. These could all increase electricity demand and substantially reduce the demand for other energy vectors such as natural gas. In New Zealand, Germany, the UK and the USA low carbon transport and homes are being promoted. In these countries there are uncertainties on the level of investments needed both to reinforce electricity networks and increase flexibility, and to upgrade the natural gas network so that it can transport low carbon gases e.g. hydrogen and biogas [96–98]. Encouraging companies to invest in upgrading energy networks or sources with an uncertain future could be a difficult task. For example, the future role of natural gas infrastructure in the transition pathways of the UK, New Zealand, Netherlands, Germany, California and Japan is very unclear [97]. Thus, the uncertainties regarding possible technological development and choices could increase the risks associated with investments in energy networks [99].

A growing area of uncertainty is around the availability and price of a range of minerals and metals that are vital for key low carbon technologies across RE generation, transmission, distribution, and storage, as well as in the transport sector. For instance, demands for lithium, cobalt, and nickel are all expected to increase since they are required to improve the performance, longevity, and energy density of batteries, while powerful magnets in wind turbines and EVs need rare earth elements [100]. Also, grid-expansion and reinforcement require more copper and aluminium, with copper demand for power lines expected to double by 2040. Since, copper and aluminium currently account for around 20% of grid investment costs, if prices were to rise in the future, then this could have a major impact on the level of grid investment [101]. Hydrogen transportation requires building new pipelines and repurposing of existing natural gas pipelines. Producing hydrogen with electrolysers and the uptake of fuel cells could drive the production and use of a few critical minerals including iridium, platinum, cobalt and nickel [100–102]. For example, one high scenario estimates annual iridium demand from electrolysers for Europe alone to be 110% of the world's annual supply [102].

A number of challenges come with these increased demands. Firstly, rare and critical minerals for the transition are not uniformly distributed, produced and processed. They are concentrated in certain countries and so, like fossil fuels, their demand and supply are prone to geopolitics. To enhance energy security, certain policies and strategies should be deployed nationally and internationally to ensure techno-socio-environmental sustainability. Investment into mining and processing of such materials should be encouraged and regulatory regimes need boosting to avoid further degrading of the environment and to address labour welfare and child labour issues [100]. Minerals are recyclable and their shocks from shortages are not transmitted immediately unlike fossil fuels; offering more time for the system to adjust. The security issues as far as mineral shortages are concerned may thus be different from fossil fuels, but there is a possibility of cartelisation which could be engineered to cause increased uncertainties in the minerals market [103]. Scientific research on the availability of critical minerals is relatively limited and more detailed analysis is needed to understand the scale of any potential shortages for not only critical minerals but for non-critical ones that are usually overlooked [104].

Most of the papers highlight the implications that decarbonising electricity and mobility will have on minerals underlying the transition, but without giving much attention to solutions such as a more circular economy [105]. However, it is clear that the energy transition requires a paradigm shift from linear economies to circular economies to reduce pressures on the environment and to ensure security of material supply [105,106]. Thus product designers and policy makers need to consider reducing, reusing, recycling and recovering materials used for production and distribution of transition related devices and infrastructure [105,106].

3.3.4. *The future of natural gas*

The natural gas network has been a key asset in many countries over the last 40–50 years. The properties of gaseous fuels (easy to transport and store, wide range of end-uses) makes continued gas use an attractive proposition in many circumstances. However, this requires a solution that can either allow continued use of natural gas (mostly methane) while substantially reducing the associated greenhouse gas emissions or finds new gaseous fuels that have low or zero carbon emissions. In the UK, Netherlands, Germany, California and Japan, among the pathways being considered is the hydrogen economy which will have significant impact on the infrastructure of the gas sector as well as end-users [107]. Another pathway is to invest in, expand and reinforce, electricity grid infrastructure to accommodate high levels of RE from wind and solar and have an electricity-dominated energy system with relatively little support from the gas network [108]. The use of Carbon Capture Utilisation and Storage (CCUS) and other technologies to reduce carbon emissions from the use of natural gas in the power and industry sectors are also being considered without being linked to an explicit pathway [109], which further increases the level of uncertainties in future investments in the sector [110]. The energy policies and climate change plans of most countries highlight these different scenarios and related threats and opportunities, but are less clear on the eventual choice. For example, analysis of gas use in Europe suggests that reducing greenhouse emissions to zero could lead to a 30–45% reduction in gas use by 2050 [111] Under such a scenario, the gas network's fixed costs would need to be recovered from fewer customers, which could have significant cost implication for future consumers or even lead to a "death spiral" for parts of the network [112]. This risk can be avoided if the network can be repurposed to transport green gases (e.g. hydrogen and biomethane) in a way that brings little or no additional cost to the consumer. As a result of such challenges, the gas networks are collaborating with the electricity networks to enable both to continue playing a significant role now and in the future market [113][see Section 4].

3.3.5. *Regulatory challenges*

With the privatisation and liberalisation of energy markets in recent years, much of the focus of network regulation has been on driving down costs and increasing efficiency. However, in some countries these regulatory structures are being adapted to have an explicit focus on incentivising investments that can support the energy transition. With electricity, it is expected that regulatory systems should be able to incentivise grid expansion and unconventional solutions to grid integration [114]. Effective application of incentives to increase investments in "intelligent solutions" is a challenge to the regulator. Key issues that regulators are having to deal with include how to increase RE; how to deal with curtailment and its compensation; and how to increase security without increasing planning costs to consumers. These issues require a systemic approach to regulation and policy making [115] and they are exacerbated by the urgency of the transition [116]. Typically network companies make network upgrades and other investments in response to a clearly identified need. However, in the UK the regulator is being encouraged to enable network companies to make anticipatory investments (known as "investing ahead of need") where appropriate so as not to hold-up low-carbon investments on both the supply and demand-side [117].

Challenges can also occur with new technologies that link two or more vectors. For instance, a power-to-gas technology whether for hydrogen or SNG (Synthetic Natural Gas) presents regulatory and legislative challenges. These include how to define the process (storage or production), the incentives, exemptions and related costs to final consumers, licensing/authorisation requirements, connection and capacity constraints and unbundling rules (cross-sector potential of P2G) amongst others [118–121]. To maximise the benefits from these new technologies, these regulatory and legislative concerns need to be addressed and this is an ongoing process in all the countries sampled, even though Germany seems to be a leading example in this respect [122].

While solutions to many of these challenges exist, they cannot be effectively implemented without dealing with the associated political and social issues [123]. As many distribution network operators have noted in Germany, incentivising unconventional measures (including storage and other flexibility services) to deal with grid integration changes how capital and operational expenses are treated in the regulatory year. For example, unconventional measures often have higher operational costs compared to grid expansion solutions, which are more capital intensive. Therefore a system that rewards capital investment may be inadequate to incentivise unconventional measures [123].

The impact on consumers and workers is of growing concern. While there is significant evidence from a range of countries about the falling costs of electricity generation from renewable technologies, yet wholesale prices, transition-related-capital and other costs are putting upward pressure on electricity prices to consumers [124]. Drivers of soaring electricity prices in late 2021 and early 2022 have resulted from a combination of factors. These include reduced investments in gas and oil production when energy prices collapsed in 2020 as a result of the Covid pandemic, combined with delayed maintenance work that started just as demand was rising again, as well as lower than usual electricity generation from wind power in Europe [125]. Wholesale electricity prices for the Nordic region, Germany and the UK for the fourth quarter of 2021 were between three and above four times higher than the 2016 to 2020 average. For Japan, the electricity price experienced just less than an 80% rise in the last quarter of 2021 when compared to the 2016–2020 average [126]. Since consumers are varied in terms of capacity to pay, low-income and vulnerable households may suffer most and some companies, with high energy costs and low profit margins, could be put out of business. In the US for example, the 25% of households who spend more than 10% of their income on energy face the highest burden [127]. For network companies, the cost of transmitting and distributing energy is expected to rise, while increased competition from distributed generators could reduce their revenue [128]. In Germany and Britain, congestion management and curtailment costs have increased and yet more investments are needed for grid reinforcement which are directly borne by network operators [129]. A further issue is the welfare of the workforce currently employed by the fossil industry and who could be severely impacted by loss of employment as a result of the energy transition. This poses the question of whether a low-carbon economy will be able to find suitable roles for the affected work force [130,131]. This issue has significant implications for society and so it is important for policymakers and others to address such impacts by engaging and retraining workers, and communicating and protecting workers' rights [130].

3.3.6. Impacts of climate change

Energy networks are critical infrastructure that are exposed to extreme weather conditions including floods, storms, heat, wildfire, and lightning. Climate change could increase the frequency, intensity and duration of such extreme weather conditions and could interrupt energy network operations [132]. It is expected that cost of planning and restoration as well as cost of unserved energy could increase which will consequently affect the economic and social wellbeing of consumers [133]. A combination of ageing network infrastructure and growing climate change impacts may increase in frequency and duration of disruptions to network operations. Some evidence for this can be seen in the experience of the USA and the UK over the last 30 years [134,135]. Increasingly weather related risks are becoming very significant in planning resource adequacy as highlighted for the US by Domah and Pollitt [136]. Approaches to improving resilience to the impact of extreme weather include upgrading components to make them more robust, employing effective operational procedures to improve supply restoration time and investing in transmission redundancy and smart grid solutions [132,133].

3.4. Energy networks innovation and policies

The literature reviewed highlights three broad solutions to the challenges identified in the previous section; increasing network flexibility and resilience through both technical and market changes, greater interconnection between networks that carry different energy vectors, and the development of new low carbon energy networks. Delivering these solutions is requiring new policies to drive the necessary innovation.

3.4.1. Increasing the flexibility and resilience of networks

Increasing the flexibility of the electricity system is key to enabling the integration of large shares of VRE. Options for achieving this that are highlighted in the literature include more flexible (fossil) fuel plants, greater use of energy and heat storage, grid extension and reinforcement, market design solutions, demand response and the use of synchronous compensators [75,137,138]. Power plants have consistently been enhanced to respond quickly to the fluctuations in the output of VRE. Lower minimum load and a quicker ramp rate form the desired qualities making it possible for thermal plants to migrate from baseload operation to an intermediate and then peaking role; with these innovations well established in the UK, Denmark and California [115]. Flexible thermal power plants for balancing and security needs remain vital in Denmark, Germany, California and the UK until other innovative technologies can replace them [139].

Looking further at the experience of individual countries, Denmark, Germany, and California are often highlighted in the literature as having been able to deal successfully with the challenges of renewable integration. In the case of Denmark, the problem is handled by using a combination of power exchanges with neighbouring countries, flexible coal plants (being phased out), flexible CHP plants integrated with thermal storage facilities, must-run-capacity, an ancillary balancing market, advanced forecasting of wind output and a reinforced power grid [6]. Germany has been successful in dealing with variations in RE outputs due to having technically strong grids, flexible conventional power plants and an over-supply of capacity [140]. The country also has a market that enhances wind power curtailment due to low price signals (with negative prices sometimes) [6]. Analyses made by the California Public Utilities Commission (CPUC) suggest that California's existing grid characteristics have allowed the accommodation of variable wind and solar with slight changes to its operations [4,105].

Electricity and heat storage have the potential to increase the flexibility of the grid. Compared to other forms of flexibility, storage flexibility is a much studied topic but currently its high costs mean that it only contributes marginally to solving grid-integration in most countries [142]. A view is held that thermal and electricity storage could contribute substantially after there is a 40% RE integration [51]. While Germany uses both electric power and heat storage, Denmark plans to rely mostly on thermal storage, along with other measures, as RE approaches 50%. California has mandated power companies to develop up to 1.3 GW of storage by 2020 as California's renewables exceed 33% [143]. However, the Danish TSO has a strategy to build system stability properties into the grid when this is economically advisable, thereby allowing the services required to be provided without co-generation of electricity.

Electricity–to-Thermal (E2T), Power-to-Gas (P2G) or Power-to-Hydrogen (P2H) and Vehicle-to-Grid (V2G) can all provide storage capabilities and therefore offer flexibility to the grid but with some regulatory, institutional and economic challenges [144,145]. With E2T, it is easier to store heat than electricity and therefore this approach can help decarbonise domestic heating using excess power from renewable sources [146]. Similarly, P2G and P2H offer opportunities for increased flexibility by using excess RE to produce synthetic methane and hydrogen, both of which could be stored, and then used later to generate power for the grid [147]. V2G can enhance flexibility by using electric vehicle batteries to discharge into the grid at times of high electricity demand, while charging the vehicles overnight when demand is low [148].

Although technological innovations are vital to solving the challenges of energy networks, the right designs of electricity industry arrangements and markets also play an important role. Therefore, market design and investment management decisions are a part of the non-technological solution to dealing with grid integration and these arrangements need to be executed holistically. This is because there are cost implications with a poor market design, necessitating impact studies before investing time and resources in any changes [149,150]. Market tools including capacity markets, balancing markets, market aggregation for geographical smoothing, power pools and bilateral markets all have different cost implications and flexibility potentials depending on the country [151].

Interconnectors can provide additional capacity, sometimes even higher than the peak demand of some countries, to offer storage of excess VRE and grid balancing solutions [152–154]. Denmark's location for example provides an advantage to utilise interconnector capacity which links the Nordic region and Continental Europe respectively [70]. A number of interconnectors within Europe exist, but the ambition of an integrated energy market in the EU has catalysed plans to extend or build more of them to connect Denmark and the Netherlands, Denmark, and the UK, as well as Germany and UK. The advantage of interconnectors regarding balancing requirements of two or more countries can be delivered while enhancing regional integration from which markets can be developed. Thus, for UK and Denmark, the Viking interconnector due in 2023 will be valuable to both countries regarding balancing, access to cheap electricity from the Nordic region, and reinforcing the European market [155]. Interconnectors in the USA are quite common at the Federal level; however, Japan and New Zealand are geographically remote, making interconnector benefits almost unachievable in the short-term. However, a recent study attempts to justify both a Japan-Russia, and a Japan-South Korea interconnector [156].

3.4.2. *Greater interconnection between networks of different vectors*

Combined Heat and Power (CHP) plants are a widespread technology that provide coupling between the electricity and heating sectors and can be used to provide an opportunity to increase integration of wind by providing flexibility. Heat and electricity are produced concurrently with an overall conversion efficiency up to 90% [157] and CHP can change the outputs of electricity and heat to suit the need and so balance both networks. Despite being an established technology, diverging energy policies and accompanying regulations have resulted in the uneven diffusion of CHP even amongst countries that have similar economic development [158]. The regulatory regime has been particularly favourable to CHP plants in Denmark and Germany through subsidies, waiver of other costs and the functioning of the electricity market [159,160].

In addition to CHP, the interactions and interdependencies of electricity, heat and gas networks are manifested in various ways. These include the role of gas networks in delivering fuel to gas fired power generating plants, and more recent technologies such as P2G, P2H, and thermal storage. The gas network is therefore a vital system that currently supports other networks, making its future in a low carbon energy system one of the key challenges confronting policymakers. Over the years, there has been growing interdependencies between electricity and gas, and even though this is beneficial, it comes with some data management, regulatory and market challenges for the networks involved [161,162]. It is worthy to note that almost all scenarios considered in future network studies still include at least one that incorporates the gas network as a storage or a transmission system. An example is the analysis of the importance of the gas infrastructure for Germany's energy transition where three scenarios are presented i.e. electricity only, electricity and gas storage, and electricity and green gas scenarios [163]. Here, with scenarios retaining the gas infrastructure, decarbonisation costs are reduced while acceptance and security of energy increases. In the case of the UK, the "evolution of gas" scenario, assumes significant utilisation of gas networks for hydrogen and other green gases and demonstrates a relatively low cost with high acceptability and limited disruption [164]. There are other future analyses of the transition that continue to highlight the importance of the gas network [165].

3.4.3. *Development of new networks*

A review of the use of DHC demonstrates that the network is still less widespread in most countries compared to electricity and gas networks. For example, the share of DH in Germany's residential sector is just 13.8% and yet this is one of the biggest markets globally (in absolute figures).

The use of CHP to feed heat networks is currently the most prevalent technology in most countries, with newer technologies, such as heat pumps, having limited deployment. This is evidenced in Sweden and Germany where over 60% of the heat generation comes from cogeneration [166,167]. The most common fuels used in CHP plant are natural gas, waste to energy, and biofuels. In the UK, DH is seriously underutilised, representing only about 2% (in 2013) of heat demand as compared to natural gas network which supplies over 80% of heat [168]. However, from the CCC's central scenario, significant expansion in DH is envisaged in the UK; increasing by six-fold by 2030 [169] and with a compound growth of 8% until 2050 [170].

The situation in the Netherlands is similar to the UK, with about 4% of heat demand supplied by district heat networks compared to 90% provided by natural gas. In the Netherlands, the use of heat pumps, geothermal and biomass are increasing as much as CHP. However, just like Sweden, the Netherlands and Denmark have a form of regulation to ensure some price control or increased competition. Germany has a liberalised heat market and DH remains an unregulated utility at the national level and is often operated by city administrators. In general, there are pricing issues with the network as it is unbundled, with less competition in generation and distribution [171]. In Japan, energy for DH is generated from wastewater temperature differentials, solid waste, refuse derived fuel (RDF), seawater, and river and ground water. Effective usage of unutilised energy from subways, underground shopping arcades, electrical transformers, and factories are the pathways that are envisaged to enhance low carbon DHCs in Japan [172].

District Cooling is even less evident than District Heating. However, as energy sources move away from fossil fuels to renewables there seems to be a rise in district cooling capacity over the years in the USA, Germany and Sweden. For example, Germany has seen an increase of 55% in DC from 2011 to 2015 and Sweden has increased trench length of DC networks from 506 Km in 2013 to 544 Km as of 2015 [173].

In the UK and the Netherlands, network companies are replacing the iron mains gas network with polyethylene pipes that will be able to transport blended gas (hydrogen and natural gas) and 100% hydrogen at low pressure [174,175]. Traditionally, hydrogen has been added or blended in small quantities (<10%) with natural gas for heating services [174,176]. Demonstration projects are on-going in the UK that are increasing the blended portions of hydrogen in natural gas. For example, the HyDeploy project of Cadent and Northern Gas Networks is testing 20% of hydrogen blended with natural gas to ensure that it is safe without changes to the stock of gas-using appliances. The H21 project led by Northern Gas Networks has shown the feasibility of having a 100% hydrogen network in the Northeast of England. In the UK especially, the future role of hydrogen has been gaining significant interest and that, with a planned approach, it can accelerate the UK's pathway to a net-zero economy by replacing natural gas in domestic and industrial heating [177]. However, the likelihood of hydrogen playing a significant role in the transition depends on its production using low carbon means; and such advancements have the potential to change the status-quo significantly [177]. The decision could also be premised on whether it will be beneficial to electrification or not, and how the value of flexibility from linepacks in hydrogen or blended gas grids compares with the cost of electricity extension and reinforcement [139,140]. Japan, USA, New Zealand and some countries in Europe have developed national hydrogen strategies with ambitious targets, including utilisation of existing gas pipelines to add high levels of hydrogen to natural gas by 2030 and 2050 [120]. However, to exploit the full potential of hydrogen, regulatory and safety challenges must be dealt with, and need to be accompanied by policies to incentivise investors and other players in the market [120]. The evidence so far suggests that climate change commitments are driving rapid developments and deployment of innovative solutions and this calls for policy and regulatory responses that are supportive and adaptive to tackle the challenges with energy networks [171].

3.4.4. *Policies to drive innovation*

A range of support policies have driven innovation in energy networks in the countries studied. The motivations for these policies are many, but often relate to national and international commitments on climate change, improving economic efficiency, and countries aspiring to becoming leaders in specific technological areas needed for a low carbon economy. The UK for instance, apart from achieving Net Zero, wants to be a technological leader in RE technologies, especially offshore wind [178] and the hydrogen economy [119,179]. Japan and California have also planned to establish a hydrogen economy and become leaders in fuels cells [180], while Germany and Denmark want to be leaders in wind energy and renewable automotive technologies respectively [181,182]. There is also recognition of specific drivers, including network flexibility requirements and the need for customers and markets to adopt new technologies for demand management [183]. Other authors have also acknowledged the disincentives that poorly thought-out regulatory frameworks can have on efficient network investments. For instance, the uncertainty in regulatory outcomes that pertain to proposed network innovation investments, and the mismatch of allowed rate of return and the risky nature of new investments, have the potential to discourage network investments [184–186]. In Netherlands, decisions on R&D policies are the responsibility of the Ministry of Economic Affairs who work with various institutions to design and implement innovation programmes. Examples include Topsectorenbeleid – a policy to promote innovation, expertise and exports in top industries including energy [187], and an Energy Innovation Demonstration grant scheme which focuses on making energy businesses internationally successful [188]. Specific R&D policies including providing grants and subsidies have led to projects aimed at enhancing flexibility such as P2H and IES. TSOs and DSOs are thus involved in the HEAVEN and IES analysis projects, which are funded through a combination of national, private or European funding [189,190]. The network regulation is designed to allow for some level of innovation investments and cost reduction even though the rewards for the former is relatively low [186].

The UK RIIO frameworks for both gas and electricity networks have stimuli for innovation and investments. They include Network Innovation Allowance (NIA), Innovation Roll-out Mechanism (IRM) and Strategic Investment Fund (SIF). The IRM allows for adjustment of allowed revenue for energy networks to roll-out trialled innovations for environmental and commercial benefits [191]. The NIA focuses on energy system transition with incidental benefits to vulnerable consumers, while the Strategic Investment Fund (SIF) aims to achieve both innovation that helps to achieve UK's net-zero targets and increase consumer benefits [192,193].

For California, aside from specific energy policies designed by Department of Energy, the network companies can use regulated revenue to invest in innovative projects subject to the performance based incentive arrangements [194,195]. In contrast, R&D in Germany is mainly funded by the Federal government even though energy networks have allowed revenue for executing some innovation projects [196]. Specific energy projects include Digital Agenda for Energy Transition Programme (SINTEG), Energy storage technologies, sector coupling and CCUS (Hy2morrow) R&D projects [186,197,198]. Denmark's innovation policies are quite similar to that of Germany since the regulatory framework does not deliberately promote specific innovation projects even though they can be accounted for as cost in the regulatory period, and R&D is mostly done through national programmes [186].

New Zealand is relatively less competitive on research and innovation and that has been taken into account in their pathway to low carbon economy [199]. Energy and carbon tax policies that are normally higher than the minimum are employed to drive efficiency and clean energy using innovative approaches. There are also specific funds for innovation and research provided by the Swedish government in partnership with the private sector. An example is the Swedish Centre for Smart Grids and Energy Storage (SweGRIDS) and KTH ACCESS Linnaeus Centre, with pilots such as Royal Seaport, Hyllie Smart City and Smart Grid Gotland.

Mcwha et al. [183] have classified network innovation policies into direct and indirect approaches. The direct policies incentivise DNOs to innovate explicitly whereas the indirect approaches employ instruments to attain a certain regulatory aim. Direct approaches provide funding to pursue development of innovative novel technologies, operating and commercial arrangements. Allowances provide specific limits as part of total expenditure, used for innovative projects, while the tendering approach is a competitive process whereby energy networks apply for funds to solve a defined problem. In addition, the rate of return for energy networks can be adjusted for them to execute specified innovative projects.

Our review reveals that most countries have realised the need to incentivise innovation in energy network operations for them to support the delivery of decarbonisation targets. Different policies and regulatory actions have been proposed or implemented to encourage a range of innovations in energy networks and a significant number of projects have been undertaken. However, it is too early to draw any lessons on which yield the best results.

4. Experience with a multi-vector energy network approach

The previous sections have reviewed the challenges facing energy networks across a range of high income countries and how they are responding. To date these responses have been largely reactive and piecemeal in nature – without an overarching approach or strategy as to how energy networks need to adapt to support a low carbon energy system. This has led to calls for a more integrated approach based on the concept of a Multi-Vector Energy Network or as part of an IES [18,19,95,200].[2] Such an approach would aim to deliver the benefits of a "system-of-systems" in which the different networks are planned and operated together to create a more complex system that offers greater functionality and performance than simply the sum of the individual networks [18]. Thus the MVEN approach can be thought of as a way to operationalise the integration of all the elements shown in the co-evolutionary framework for the energy transition (Fig. 1) across different energy networks.

4.1. Benefits of an MVEN approach

An MVEN can be beneficial if it can eliminate or reduce some of the challenges identified in this paper (Section 3.2) or enhance the responses (Section 3.3) in a way that is technologically feasible, but also economically, environmentally, and socially acceptable. Common drivers for investigating an MVEN approach include exploiting the large wind and solar energy resources in many countries by providing grid integration solutions and so avoid or reduce costly curtailment of VRE [70,201,202]. Other studies are motivated by the advent of new energy conversion and transfer technologies, such as P2H and P2G, leading to the need to co-plan and co-optimise two or more energy networks [203–205]. Moreover, a number of studies highlight the scope for new business models and services as countries embark on integrating and managing energy networks together, but that this will also require an evolution in regulatory structures [19,95,206].

Lower costs and improved social welfare. Evidence suggests that, as compared to isolated networks systems, MVENs can reduce the cost of operations. A number of studies [18,95,207,208] have demonstrated or highlighted cost efficiency during both planning and scheduling phases and/or the energy conversion and storage phases of IES managed together in energy hubs. He at al [209] found that an integrated planning approach between electricity and gas networks can deliver about 20% peak shaving, with significant economic benefits on the level of investments needed to sustain the networks. While Hosseini et al. [210], in their simulation experiment, found increased reliability and a decreased carbon footprint, but network operation costs increased. In addition, MVENs can increase competition between different energy sources, so enhancing social welfare by delivering lower prices to consumers and minimising operational costs [211–213].

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[2] MVEN and IES are both terms used to describe the coupling and interactions between energy systems at various scales (from multinational, national, community scale down to building level). MVEN is specifically concerned with the network aspects of these interactions, whereas IES covers the whole energy system from energy production, energy supply networks, down to consumption. In contrast, smart energy systems describe the way in which more and different forms of data are collected and used, fusing energy systems with information systems, and allowing energy system objectives to be met in more effective ways.

Reduced curtailment of variable renewable energy. Several studies [214–218] suggest that MVENs can lead to a reduction in curtailment of VRE during periods of high supply or low demand. This yields lower operational costs to investors and lower prices to consumers. Where grid extension and related investments are considered as a remedy to VRE curtailment, P2G technologies incorporated in MVEN planning and optimisation could avoid it with the potential to use storage capacities in the gas network in the form of line-packs [208,218–221].

Improved energy efficiency. A number of studies have demonstrated increased system efficiency owing to the synergistic advantages of MVENs during planning and scheduling, eliminating grid extension and its associated power losses as well as the production of new gases or fuel (e.g., methane and hydrogen). For example, Devlin et al. [222] using the UK and Ireland as an example, show that the natural gas and power systems when co-optimised can decrease gas generation output by 5.48% - providing energy savings and cost reduction. Other studies including [216,223–225] have also demonstrated and evidenced cost savings, increased energy efficiency and a good performance of IES. For example, Zhang et al. [226] posit that the increased energy efficiency of MVENs is due to the integration and utilisation of surplus energy, and the decrease in power losses.

Higher quality of energy provision. Improvements to flexibility, security and/or reliability have been found in many studies of MVENs [206,225,227,228]. Li et al. [229] found that operational performance and flexibility are improved with additional benefits. For instance, in their simulation exercise, coal usage reduced by 20 tonnes per day while absolutely ending wind energy curtailment. Zhang et al. [226], modelled electricity and heat networks at both local and national levels in the UK, and demonstrated increased investments in heating infrastructure that culminated in increased flexibility under an MVEN system. Similar conclusions are drawn by Devlin et al. [222] where the gas and electricity networks of Great Britain and Ireland were modelled together under various weather extreme conditions, and found benefits of increased system flexibility and resilience due to MVEN interactions and interdependencies.

Reduced emissions. Compared with single/decoupled vectors, a MVEN approach can reduce carbon emissions levels [209,210,225,230,231]. Though studied at different levels and/or scales, a significant number of the papers involving P2G and P2H technologies suggest a possible reduction in carbon emissions and hence an environmental benefit from MVENs. Both technologies allow direct synergies to be exploited leading to high integration of RE sources, and resulting in a system of low carbon emission [208,230,232–234]. According to Zhang et al. [223], MVENs will encourage the use of P2G with improved payoff when used for ancillary services including carbon emission reduction and provision of secondary reserves.

4.2. MVEN challenges and the way forward

The evidence on challenges have been well documented in terms of IES [225] and seems to agree well with those revealed by the literature we have reviewed thus far on MVENs. Three broad categories of challenges have emerged and are discussed accordingly in this section.

Markets and Institutional Arrangements, Regulation, and Standardisation: Synchronising market rules and regulatory regimes for two or more networks is an under-researched area making it difficult to identify specific MVEN challenges. However, it is clear that the current fragmented markets and institutional arrangements will need to be reorganised to facilitate MVEN approaches. This may encounter initial conflicts, but these should be resolvable through collaborations between all parties [235]. Wang et al. [236] identified that participation in collaborative or coordinated optimisation, planning and scheduling in two or more IES is premised on benefits to the whole system, but also the individual sub-systems. Like MVENs, it is inferred that some networks (sub-systems) may have to sacrifice self-interest for the optimisation of the whole system. Inequality in the sharing of benefits requires a rather more complex collaborative optimisation technique, supported by equally sophisticated market and regulatory arrangements, to ensure appropriate incentives for participating in the collaboration.

The literature on Codes and Standardisation on MVEN components is not sufficiently well developed, as such discussions at the policy level have only recently started and are currently limited to a few jurisdictions. Specifically, developing standards on MVEN energy conversion and transfer technologies that link the networks are at a rather early stage. One important area for further work highlighted in the literature concerns the interchangeability of gaseous fuels (methane from fossil and biogenic sources, hydrogen, blended gases etc.) and gas quality requirements in MVENs [212]. Such challenges of storage and conversion technologies are being considered by the European Commission. This has highlighted that, though some of the standards and regulation can be interpreted from existing regulations, P2G (hydrogen gas and SNG) and CCUS lack specific rules or legal guidance [237].

Complex modelling, Sharing and Quality of Data, and Risk Challenges: To date studies that use modelling and analyses have dominated the MVEN field. They are usually conducted with different configurations of networks and at various scales and levels. While there is ample evidence at local and regional levels, research on MVENs with cross-border interactions are few and this does not reflect the real-world trend towards regional market integration. Thus Devlin at al [222] recommend that an integrated European gas and electricity model is needed to explore the value of both power and gas to the other sub-system as the EU transitions to single power market.

Notably, there is less evidence of practical demonstrations of MVENs, which are needed to help reduce the perceived risks associated with the novel ideas, strategies and technologies involved. These risks can impact negatively on investment decisions. Also, the lack of commercial tools to design, plan and operate networks is a limitation to maximising the benefits that are expected from a MVEN [225]. Some authors, including Shabanpour-Haghighi et al. [213], have cited computational difficulties in certain modelling approaches that are used in the optimal energy flow problems of distributed generation. Data availability for modelling, planning energy supplies and investments; operationalising and regulating energy markets poses challenges in many cases. In terms of operation, there needs to be trust among parties so that data is made available complemented with an effective data sharing platform where systems can interoperate yet assure data protection. High quality and timely data is needed for system optimisation and market operations [95]. Therefore, Wu et al. [225] suggest that powerful software is needed to uncover the sophisticated interoperability elements to enable modelling and analysing MVENs in order to avoid cascaded failures.

Limits on MVEN Cost and Benefits Analysis: The lack of practical studies on the interactions between and within networks at various levels of energy supply (e.g., V2G) is a limitation as there could be cost and environmental inefficiencies that may erode the benefits of MVEN demonstrated so far. So far few studies have explicitly incorporated the role of demand response (thermal and electrical loads) in MVEN analyses, and the uncertainty caused by this additional flexibility on the system could further complicate models that aim to co-optimise the planning and operation of multiple energy networks [211]. Regulatory challenges are likely given that the frameworks have been traditionally developed independently without considerations for intersecting boundaries. If systems increasingly interact and open up for new entrants and business models, more research will needed to evaluate the real impact of MVENs. This could include weighing benefits, such as increased flexibility, and the disadvantages of possible stakeholders' concentration if some roles and functions are combined across vectors [206], besides the cascading effect of faults from one subsystem to another [95,238]. Greater interconnections and interdependencies between networks could increase or escalate operational risk and therefore security awareness must be improved using robust security tools [239]. For instance, Li et al. [240], and other studies, have identified and tested “security regions” and seem to show satisfactory accuracy of determination. However, the modelling of these security regions with multiple constraints remains a challenge and this should be much explored or investigated in a multi-dimension space to improve the monitoring and potential of MVEN.

Finally, while the techno-economic and environmental aspects of MVENs are quite well researched, investigations regarding the "people factor" relating to awareness, acceptability and societal impacts are less common. Therefore, more research is needed on this topic given that MVENs, just like any other integrated system, depend on the cooperation of multiple stakeholders who have vested interests, and different political and economic incentives. Difficulties can be foreseen in balancing the need to increase stakeholders' engagement, while aiming to employ non-trivial strategies [241]. Nonetheless, there is evidence that stakeholders impact profoundly on energy planning scenarios [242, 243]. Furthermore, stakeholders' views on MVEN and IES approaches were absent from the papers in our review, implying that this could be perceived as less relevant. Similarly, policy papers on MVENs were almost absent. Given the uncertainties surrounding acceptability and the lack of practical evidence on MVENs, it is vital that policymakers begin to formulate plans at the national, regional, and local levels for practical demonstrations.

5. Conclusions

Energy networks are at the heart of the energy transition that is taking place across the world. However, the challenges these networks face, and the potential solutions, are often overlooked with most studies focusing on developments in the power sector and some end-use sectors, such as heating and transport. In this review we seek to highlight how energy networks are changing in key high income countries in response to energy policy priorities and developments in the wider energy system. We find that countries have a diversity of starting points in terms of the current ownership models for energy networks and their regulatory structures. In many cases private actors play a key role in planning and operating energy networks, with government providing the regulatory framework and this model, which has historically focussed on cost efficiency, is being challenged by the need to make significant investments to help facilitate the transition to a low carbon economy.

Our review revealed four key technical and economic challenges that are shared to a greater or lesser extent by energy networks in all the countries we reviewed. The first is the integration of large quantities of VRE into the electricity system, leading to the need for increased flexibility while minimising reliance on back-up fossil fuel generators. Second, is the increased use of low-carbon electricity as climate mitigation strategy in end-use sectors, such as transport, heating, and industry. This has impacts not just on the volume of electricity that must be transported by the transmissions and distribution system, but also may increase peak loads by an even greater extent and so reduce the utilisation of the network assets. Third, it is becoming clear in many countries that currently rely on natural gas for heating in homes and industry that this vector does not have a long-term future in these roles. Either the gas network must be adapted to transport new low carbon gases, such as hydrogen, and/or it will see decreasing volumes of gas being transported as many traditional end-uses for gas are electrified. The final challenge is planning and regulating networks for the future in the face of considerable uncertainty. For many countries it is not clear how the balance of electricity vs natural gas vs hydrogen vs DH will develop over the next 30 years. Yet, networks are being tasked with being an enabler of these changes – which are often identified as being urgent – with little idea of exactly which energy future they are being asked to help deliver.

Currently, the response to these challenges is rather piecemeal in all the countries we reviewed. Many countries have innovation and other policies to support changes that will be needed. For example, new technologies, such as energy and heat storage, P2G, and P2H are starting to be deployed to increase the flexibility of networks. Some networks, such as DH, are being expanded, while trials are ongoing in some countries to see how others, such as natural gas, can be repurposed to carry hydrogen. There is also a greater interconnection between networks, but this is often because of changes on the demand-side (e.g., electrification of heat) or in response to a specific need for flexibility (P2G) rather than as part of a broader strategy. Furthermore, insufficient attention has been given so far to the societal implications of these changes.

The challenges facing energy networks have led to calls for a more integrated response, known variously as an MVEN or IES approach. Under this concept, the planning and operation of energy networks would be undertaken in a holistic way, enabling a seamless integration between networks carrying electricity, gas, and heat. Numerous simulation-based studies at various scales and levels and using a variety of modelling techniques have explored this concept. Most are broadly favourable, finding a range of benefits from lower costs, greater flexibility, greater energy efficiency, higher quality of energy provision and lower emissions. However, these models implicitly only consider idealised conditions and, to date, studies demonstrating the practical application of MVEN/IES approaches to verify the costs and benefits are lacking. We believe there is a compelling case for countries to explore how such approaches can be implemented practically. This should include improving our knowledge about the appropriate regulatory and policy structures to incentivise greater co-ordination, to verify the benefits identified by modelling studies, and to identify how any problems can be mitigated, such as the risks of failure in one network cascading across vectors and so bringing down the whole system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix

Table 4
District heating market and regulatory structure.

	Ownership	Level of Integration	Regulatory Authority	Regulatory System/Tariff Setting	Legal Framework
Germany	Municipal (Stadtwerke) and Private, Private-Public Partnership (mixed ownership)	Vertically integrated -few TPAs	No regulatory body: competition law brings some level of consumer protection-an oversight of the Competition Authority	Liberalised; ex-post regulation of end-user prices at local level (self regulation); TPAs are guaranteed to enhance competition.	Ordinance on General Conditions for the Supply of DH (AVBFernwärmeV)- Federal level governance.
Denmark	Market is dominated by municipal ownership but also with some consumer -owned enterprises	Less vertically separated	Danish Utility Regulator (Forsyningstilsynet)	Regulated; Cost-plus regulation; mandatory connections for new build.	Heat Supply Act (1979)
Sweden	Diverse ownership (municipal and private)	Vertically integrated with possibility of TPAs negotiations	Energy Markets Inspectorate and Competition Authority	Liberalised, Unregulated	Light-touch regulation under the District Heating Act (2008)
The Netherlands	Mostly privately-owned and some are owned by the municipal	Some are vertically integrated; Heat is also purchased through TPAs	Authority for Consumers and Markets (ACM)	Regulated, price-capped by average household for gas heating or alternatives (for vertically integrated heat networks	Heat Act (2014)
Japan	Municipal ownership with TPAs	Vertically integrated	Ministry of Economy, Trade, and Industry (METI), Natural Resources and Energy, Electricity and Gas Market Surveillance Commission	Self-regulating	Heat Supply Business Act (2015) Renewable Energy Act (Act on sophisticated methods of energy supply structures on RE heat)
California (USA)	Public utility owned with few investor-owned networks	Highly vertically integrated	California Utility Regulatory Commission	Cost of Service/ Competitive or Unregulated	Federal Policy Action on S1711- Heat Efficiency through Applied Technology Act (HEAT 2017) Federal Policy Action on S1851-The Advancing Grid Storage Act (2017) California building code (2019)
New Zealand	Dominant Community Trust and Municipal Ownership	Vertically integrated	MBIE	Cost plus unregulated	Resource Management Act
United Kingdom	Mainly -Public-Private ownership-Municipal ownership is uncommon	Vertically integrated	BEIS (Project Licensing function) Ofgem (although Industry plays a role in designing codes)Office for Product Safety and Standards (OPSS)-appointed by BEISHeat TrustChartered Institution of Building Services Engineers (CIBSE)	Unregulated	The Heat Network (Metering and Billing) regulations 2014Heat Trust guidance (voluntary)CIBSE codes (voluntary)

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