An Interdisciplinary Research Perspective on the Future of Multi-Vector Energy Networks

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Abstract: Understanding the future of multi-vector energy networks in the context of the transition to net zero and the energy trilemma (energy security, environmental impact and social cost) requires novel interdisciplinary approaches. A variety of challenges regarding systems, plant, physical infrastructure, sources and nature of uncertainties, technological in general and more specifically Information and Communication Technologies requirements, cyber security, big data analytics, innovative business models and markets, policy and societal changes, are critically important to ensure enhanced flexibility and higher resilience, as well as reduced costs of an integrated energy system. Integration of individual energy networks into multi-vector entities opens a number of opportunities, but also presents a number of challenges requiring interdisciplinary perspectives and solutions. Considering drivers like societal evolution, climate change and technology advances, this paper describes the most important aspects which have to be taken into account when designing, planning and operating future multi-vector energy networks. For this purpose, the issues addressing future architecture, infrastructure, interdependencies and interactions of energy network infrastructures are elaborated through a novel interdisciplinary perspective. Aspects related to optimal operation of multi-vector energy networks, implementation of novel technologies, jointly with new concepts and algorithms, are extensively discussed. The role of policy, markets and regulation in facilitating multi-vector energy networks is also reported. Last but not least, the aspects of risks and uncertainties, relevant for secure and optimal operation of future multi-vector energy networks are discussed.

Keywords: Energy markets, information and communication technologies, modelling, multi-vector energy networks, policy, risk.

List of abbreviations:
CCGT - Combined Cycle Gas Turbine
CCS - Carbon Capture and Storage
CIG - Converter Interfaced Generation
CHP - Combined Heat and Power
DER - Distributed Energy Resources
DLT - Distributed Ledger Technology
DNO - Distribution Network Operator
DSO - Distribution System Operator
DSP - Digital Signal Processing
ETL - Extract Transform Load
EV - Electrical vehicle
FICTP - Flexible ICT Platform
GBSO - Great Britain System Operator
GHG - Green House Gas
ICT - Information and Communication Technologies
MVEN - Multi-Vector Energy Network
M-SAT - Multi-Energy Networks Situational Awareness Tool
P2G - Power to Gas
SNG - Synthetic Natural Gas
TNO - Transmission Network Operator

1. INTRODUCTION

Energy networks form the backbone of energy systems and are vitally important enablers in the global pursuit of a just transition to net zero [1]. Energy networks have a key role to play in achieving the goals set out in the Paris agreement of 2015 [2], commited to by many countries from across the globe, and to deliver a green recovery from the COVID-19 pandemic [3]. Energy networks exist primarily to exploit and facilitate temporal and spatial diversity in energy production and consumption and to take advantage of economies of scale where they exist. The transition to net zero and the energy trilemma (*energy security, environmental impact and social cost*) present many complex interconnected international challenges.

These challenges vary considerably from region to region due to historical, geographic, political, economic and cultural reasons. As technology and society changes, so do these challenges, and therefore the planning, design and operation of energy networks needs to be revisited and optimised. Current energy networks research does not fully embrace a whole systems approach (defined as research that explores the "social, environmental, and economic impacts of energy pathways and choices, as well as the challenges surrounding technological innovation" [4]) and is therefore not developing a deep enough understanding of the interconnected and interdependent nature of energy network infrastructure [5], [6]. This paper provides a novel interdisciplinary perspective intended to enable this deeper understanding.

For the purposes of this work, energy networks are defined as the infrastructure that is required to transport energy (in time and in space) from a point of production to a point of consumption. This definition is not restrictive, and so energy networks includes electrical power transmission and distribution networks, gas transmission and distribution networks, heat networks, as well as associated ICT networks. The energy networks community, which includes individuals or institutions who are working on energy network infrastructure, would strongly benefit from a more diverse, open, supportive membership with representation from many disciplines beyond traditional engineering (such as Computing Science, Statistics, Sociology, Anthropology, Geography, Economics and Applied Mathematics) to help enact a whole systems approach. For example, anthropologists are investigating how energy systems and networks are conceptualised, the role of states, societies, communities and individuals in interacting with and shaping them, which can provide new insights useful for the design and operation of energy networks and the associated socio-technical transitions required to reach net zero [7], [8]. A deeper level of understanding, through a whole systems approach, is necessary in order to understand how best to plan, design, integrate, regulate and operate energy networks and their associated markets in the future [9]. The expected benefits would be enhanced flexibility and higher resilience, as well as reduced costs of an integrated energy system.

The energy sector worldwide is facing considerable pressure arising from the growing demand for clean energy, the need to reduce carbon emissions substantially while adapting to the inevitable impacts of climate change and coping with the depletion of fossil fuels and geopolitical issues around the location of remaining fossil fuel reserves. These pressures have implications for our energy networks. Electricity systems are facing technical issues of bi-directional power flows, increasing long-distance power flows especially for cross-country and cross-continent interconnections (upscale), and a growing contribution from converter interfaced generation (CIG) [10]. Natural gas systems in many countries have challenges of radically different business models in the face of the risk of becoming obsolete but could be repurposed to play an important role in the integrated multi-vector energy networks (cross vectors). Heat networks in many countries have little energy demand market share, although they have been successfully installed in some northern European countries, but they are being integrated with local energy resources and local electricity and gas networks to formal smart local energy systems (downscale), e.g. in Denmark [11], [12]. Other energy vectors such as hydrogen or bio-methane show great promise but as yet have no significant share of the market [13].

Facing these pressures, to be fit for the future, the modernisation of energy networks technology, processes and governance is a necessity. For example, in Great Britain (GB), it is estimated that between 2014 and 2021 £34 billion of investment across electricity networks and £7.6 billion across gas networks will be required to ensure energy demand will be met in a cost effective, clean and secure way [14]. After years of incremental changes in energy networks, transformational shifts are now becoming visible, especially in terms of downscale and upscale perspectives and cross vectors (integrated multi-vector energy networks). These are being driven by the evolution of societal norms, climate change and technology advances, and necessitate the following urgent and timely programme of research. This is briefly discussed below.

1) ***Downscale – Local Balancing of Power and Energy***. Balancing power and energy within a local network (e.g. through Peer to Peer energy systems, flexible demand like EVs and energy storage) is seen as a solution to significantly increase the hosting capacity for distributed energy resources in local grids, and to trade or share energy among local prosumers so that the reliance and the pressures put on the external energy networks will be reduced. This is creating new technical challenges, e.g. development and application of new types of flexible power electronic devices, and bringing new business models, including the transition from Distribution Network Operators to Distribution System Operators in some countries. Local balancing has the potential to change the paradigm of the whole energy system.

2) ***Upscale – Enhanced Transmission Network Interconnection***. Interconnections of wide area transmission networks have been implemented in many countries (i.e. electricity and gas transmission networks; heat networks are local so not included), and enabled trading of high volumes of energy across great distances. Uncertainties in global and European energy systems, result in difficulties in making optimal investment and operation decisions on the gas and electricity transmission networks. There are clear needs to investigate the challenges brought by enhanced network interconnection [5], [6].

3) ***Cross Vectors – Integrated Multi-Vector Energy Systems***. Although research has started to investigate the modelling and planning of multi-vector energy networks, there are still enormous research challenges in this area. The complicated interactions and interdependencies between energy networks (technical, economic and market) need to be clearly understood; the roles of gas and heating/cooling networks in the future energy systems need to be further clarified; new methodology and assessment tools need to be developed to better understand cascading failures, vulnerability and resilience; the fragmented institutional and market structures of different energy systems need redesign to realise the benefits of synergies between energy networks.

Mechanisms for improving the system operation in terms of its flexibility and increased utilization of renewable energy resources should be understood. There are different challenges in each of these three areas regarding systems, plants, physical infrastructure (e.g. cables and pipes), sources and nature of uncertainties, ICT requirements, cyber security, big data analytics, innovative business models and markets, and policy and societal changes.

This paper provides a novel interdisciplinary perspective which discusses the future of multi-vector energy networks in the context of the transition to net zero and the energy trilemma. Section 2 introduces the framework for investigation of interfaces between modelling, policy, markets, ICT and risks in multi-vector energy networks, to introduce each of the key components of the energy system that are required to reach net zero. The remainder of the work then considers each of these facets of the whole energy network system in turn. Section 3 discusses the integrated physical multi-vector energy infrastructure and the emerging research foci to demonstrate the challenges and opportunities of these interlinked systems. Section 4 focuses on ICT and data analytics, to highlight how this will be a key enabler for flexible and resilient multi-vector energy networks. Section 5 discusses the role of policy in facilitating the multi-vector energy networks alongside the economic and societal implications, whilst Section 6 introduces the market and regulatory arrangements. Section 7 covers the aspects of risks and uncertainties, to illustrate the importance of the development of suitable methods to allow for secure and optimal operation of future multi-vector energy networks even as systems rapidly decarbonise. Salient conclusions are then drawn in Section 8.

2. UNDERSTANDING, SHAPING AND CHALLENGING

A framework for investigation of the interfaces between modelling, policy, markets, ICT and risk has been developed and applied to address the overarching research question "*What is the value of a whole systems energy networks approach*?" and in particular, "*What is the value of network integration across multiple energy vectors*?" [15]. This is illustrated in Figure 2.1.

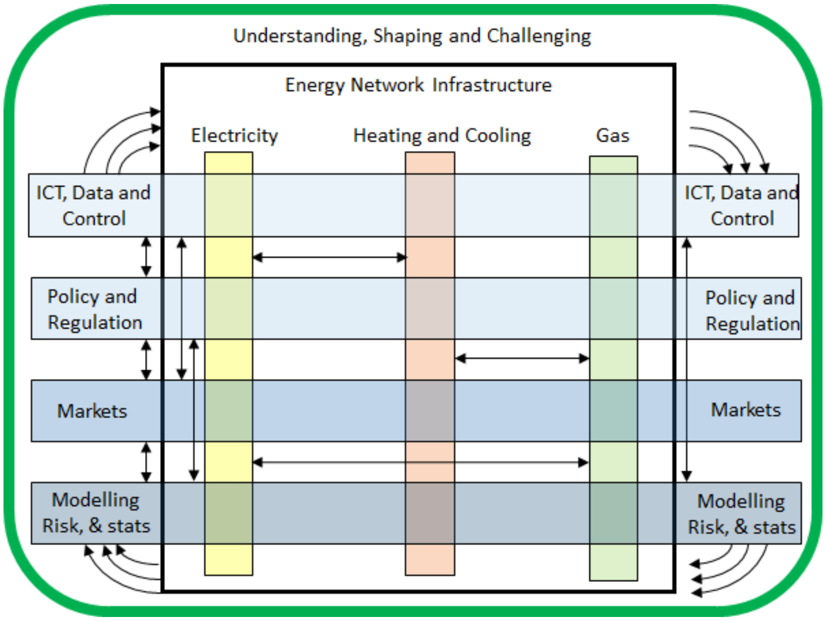

Fig. 2.1 Block-diagram of the framework for investigation of interfaces between modelling, policy, markets, ICT and risks in multi-vector energy networks

Initially, the development of the framework focused on building up an interdisciplinary, comprehensive understanding of the tools, techniques, common language, models and data sets that exist or are still required to be developed/improved. This has involved horizon scanning across the whole energy networks sector, and the sharing of definitions and quantifications, which is particularly relevant for sharing of models and tools. Once that common understanding was developed, the research team used this framework to consider the potential **shape/architecture** of future energy networks, and potential **challenges** to the networks. These will be discussed in more detail in this Section.

2.1. Potential Future Energy Network Architectures

One scenario of interest is ***Architecture 1 (A1): Bulk transnational energy transmission networks***. This possible future architecture is an integrated energy system that is national and transnational such that generation, demand and storage are mainly located long distances apart, but interconnected through energy networks. This network architecture would likely exist in a centralised governance future with lower levels of public involvement in decision making regarding energy infrastructure. This model could reduce or remove the value/role of heat networks. This means that the scale of the assets managed by a single entity is likely to be large, with power ratings of individual components being at the scale of 500 MW and bigger, and the energy of storage devices being as great as 200MWh. These systems would be facilitated by transnational markets and possibly by a small number of large suppliers. Interactions between gas and electricity networks would be very important in this model, the interactions at the transmission level would be a focus. Generation sources such as nuclear, offshore wind and gas with carbon capture and storage could dominate.

This investigation was initiated by first considering the national and transnational network architecture, with a review of the current role, and potential role, of interconnectors. In particular, one place that is of growing interest is the role of interconnectors in capacity markets – for example GB interconnector total capacity will almost double to almost 20% of peak demand within the next five years, and as such, they contribute to GB system security substantially.

There exists a patchwork of different capacity mechanisms in countries across the EU [16], and methods that can determine interconnector security contribution continue to be developed [17], [18]. Within the GB system, £700 million was allocated in the most recent four-year ahead capacity auction, with the allocated portfolio including renewables, demand side response, and interconnectors. Methods for calculating the capacity market value of dispatchable thermal plant are typically straightforward, simply being based on historic forced outage rates to determine a de-rating factor. Correlations between meteorological conditions and demands can be used to determine the de-rating factor of renewable generators, and their subsequent capacity value [17].

On the other hand, determining the capacity value of an interconnector is much more challenging [19]-[21]. This is not least due to the bidirectionality of interconnectors, which can both import and export. Correlations between net demands of different systems could lead to reduced overall system security, as resultant system stress could lead to flows acting in a direction that is contrary to their 'normal' flow. There is precedence for this – for example, the high temperature sensitivity of the French system resulted in the IFA interconnector exporting to France throughout 'Beast from the East' winter storm in February 2018 [22].

Architecture 2 (A2): Regional and service based energy networks is the second possible future network architecture configuration which was investigated. The research considers an integrated energy system that is regional such that generation, demand and storage are all co-located within the energy networks. This means that the scale of the assets managed by these entities is likely to be relatively small compared to the sizes of assets considered in the Bulk Transnational (A1) architecture. Ratings of 30MW, 10MWh might be expected to be an upper limit for the power- and energy-ratings of any assets that are managed, respectively. This architecture would likely exist in a devolved governance future with higher levels of public involvement in decision making regarding energy infrastructure. For example, heat and transport-based domestic devices have been shown to be effective at reducing network congestion [23]. Early work on this topic has investigated the impact of rapid electrification of heat on regional electricity networks, by utilising historic gas demand data. The work is intended to provide a data-driven complement to popular generative heat demand models, with a particular aim of informing regulators and actors in capacity markets as to how policy changes could impact on medium-term system adequacy metrics [24].

The third and final network architecture configuration which has been investigated is ***Architecture 3 (A3): Differentiated and blended architectures*** of energy provision. This possible future network architecture leads to variations in energy provision and therefore could be a mix of the previous two network architecture shapes. The research has explored the notion of providing different customers, regions and sectors (residential, industrial and commercial) with differentiated levels of energy service, potentially through a platform such as a peer-peer energy trading system [25]. This could be differentiated in terms of quality of delivered energy, e.g. network harmonics or calorific value, or reliability of service. Network architectures which could be used for this energy service provision were also considered, gas grid or no gas grid, regional or national and transnational. The markets are also considered as differentiated, to facilitate these envisaged methods of service differentiation. There will be vital choices, in this possible network configuration, regarding the use and importance of transmission and distribution networks across the energy vectors. Findings have been discussed by an independent expert group, Network Architecture Working Group. Table 2.1 summarises the key characteristics of these possible energy network architectures.

Table 2.1 Key characteristics of illustrative energy network futures

Bulk transnational energy transmission networks (A1)	Generation, demand and storage are mainly located long distances apart	Centralised governance future with transnational markets	Interaction across vectors more important at transmission level
Regional and service based energy networks (A2)	Generation, demand and storage are all co-located within the energy networks	Potential development of local markets, with a devolved governance landscape	Interaction across vectors more important at local, distribution level
Differentiated and blended architectures (A3)	Customers, regions and sectors receive differentiated levels of service	Differentiated markets	Interaction across all scales possible

2.2. Potential Future Energy Network Challenges

This stage considers external factors which may lead to significant change in the expected way that energy networks are planned and operated.

Challenge 1 (C1): Societal Shifts. This challenge considers the impact of major societal shifts on energy networks. These societal shifts could include changes in the workplace, considering how, where and when work is undertaken. It could include reduced car ownership combined with procuring mobility as a service. It could include how technology is used and our willingness to share data. At the time of writing, the COVID-19 pandemic is leading to unprecedented societal changes, with school closures, significant numbers of individuals working from home, and much reduced industry and commercial energy demand, for example. After the work-from-home instruction, issued from the UK Government on the 18th March 2020, and national lock-down on the 23rd March 2020, electricity demand data (see Figure 2.2) has fallen relatively sharply.

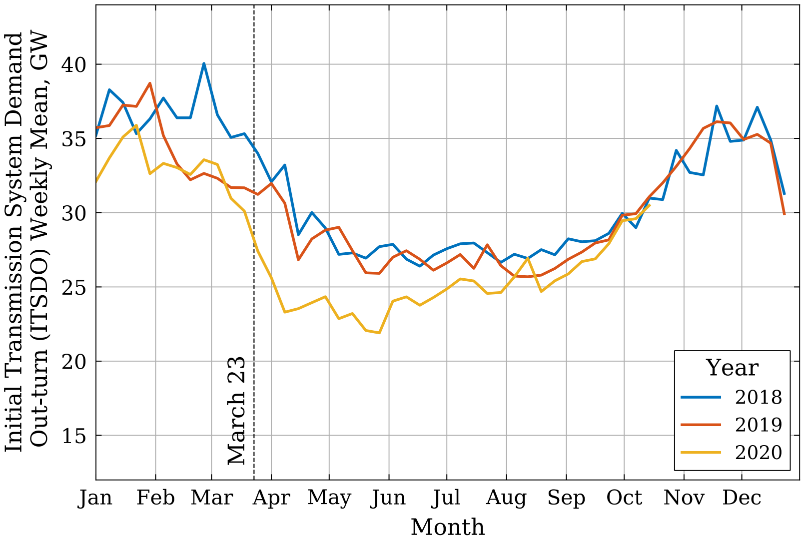

Fig. 2.2 Elexon ITSDO weekly mean demand data for 2018, 2019, 2020, showing the GB lockdown start date of 23rd March 2020

Challenge 2 (C2): Climate Change. This challenge considers major changes caused by climate change and their impact on energy networks. Climate change could affect the extreme weather events that networks experience, such as flood, wind, drought and temperatures; this would affect resilience and reliability. The same climate effects could also cause mass migration which would change the locations of load centres. The changing climate could affect energy consumption patterns, e.g. air conditioning load, heating load. Climate change could also affect renewable energy resources and their practical exploitation. Research outcomes from this work have been presented to an independent expert Climate Change Working Group.

Challenge 3 (C3): Technology Change. This challenge considers major changes due to technological breakthroughs in either energy generation, demand or network technology with a focus on their impact on energy networks. Examples could be superconductivity, mass hydrogen deployment, fusion and CCS. Another example would be that advanced digital technology deployment causes cyber security to become a significant problem.

3. MULTI-VECTOR ENERGY NETWORKS (MVENS) INFRASTRUCTURE

Conventionally the different energy networks had relatively few interactions and were designed and operated independently. However, these diverse systems are increasingly interconnected with each other via network coupling technologies, e.g. Combined Cycle Gas Turbines (CCGT), Combined Heat and Power units (CHP), Power to Gas equipment (P2G, e.g. using excess renewable energy to produce hydrogen, which can be injected to the gas network or converted to synthetic natural gas (SNG) and then injected into the gas network) and heat pumps [5], [9], [26]. The interactions mainly take place through conversion of energy between different energy systems in order to provide services and ensure that each system is managed in an optimal way. There is another type of coupling component which will consume one type of energy but will keep another energy system working properly, e.g. electric compressors in the gas networks and the circulation pumps in the district heating networks. An example of an integrated energy system with coupling components between different energy sectors is shown in Figure 3.1. Information and communication technologies (ICT) also play a critical role in such integrated energy systems, which will integrate various energy system through information sharing and coordinated operation.

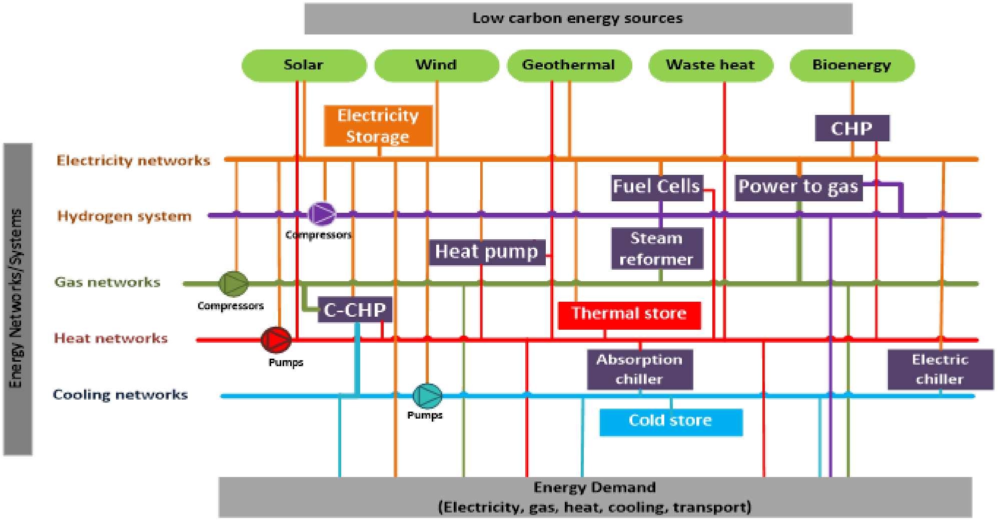

Fig. 3.1 A conceptual illustration of the integrated multi-vector energy infrastructure [27]

The key drivers for integrating various energy networks include:

- co-evolution of multiple energy systems which significantly increase the interactions and interdependencies between different energy carriers;
- integration of ICT with energy systems;
- emerging energy service companies which will design, construct, operate and manage multiple energy infrastructures together; and
- emerging flexible energy trading (e.g. Peer to Peer energy trading) and new energy markets.

In addition, the massive opportunities in research and innovation are also driving the fast development of this area.

The integrated energy system can bring a number of benefits, which mainly include:

- better use of the complementary advantages of various energy systems for system design and operation;
- carbon emissions reduction by increasing the whole system energy efficiency and flexibility;
- facilitating the integration of local sustainable and renewable energy resources;
- reduction or delay of operational and capital expenditure on energy systems;
- cost effective provision of flexibility to the electric power system;

- improved system reliability and resilience; and
- opportunities for business innovation.

There are a number of concepts and methods available around this topic, e.g. Multi-Vector Energy Systems [28], Multi-Carrier Energy Systems [29], Integrated Energy Systems, Sector Coupling and Energy Systems Integration [30], which have obvious overlaps and slightly different focuses.

After years of incremental change in energy supply networks, transformational shifts are now becoming visible. Technical, commercial and societal factors are driving the changes that can be seen internationally. There have been great developments in EVs, battery storage, solar roofing, active network management, demand response, new commercial frameworks including DNO to DSO transition, TNO-DNO integration, new ancillary services, local markets, community energy and aggregators.

However, the research in this area is still siloed in individual sectors and faces significant challenges. The key research challenges include:

- Interactions and interdependencies between different energy vectors and between different scales are complex and poorly understood in a holistic way;
- Few commercial tools are available to analyze and optimize integrated multi-vector energy network infrastructure (electricity/gas/heating/cooling networks);
- The multi-party benefits of improving the reliability and reducing uncertainties of energy supply through integrating energy systems need to be investigated and quantified;
- It is unclear how to support the whole-system integration through advanced ICT and data analytics;
- The fragmented structure of the energy supply sector and lack of large integrated municipal utilities has impeded the development of integrated energy systems. Market and regulatory frameworks are not designed for integrated interdependent energy systems; and
- It is unclear what is the best way to facilitate the development of new security, quality and design standards through detailed integrated energy network modelling and analysis.

There are a number of emerging research foci in the integrated multi-vector energy infrastructure.

1) ***Identification and quantification of the interdependencies and interactions of energy network infrastructure***. The complex links, interdependencies and interactions of energy network infrastructure need to be investigated using a holistic method, from the individual buildings, through community energy systems and national networks, to the pan-Europe energy supply networks. Methodologies are still being developed to identify and quantify the impacts of these interdependencies and interactions, considering the physics of the networks (detailed electricity power flow, pipe flows and thermal dynamics) and the technological aspects of the coupling components (such as heat pumps, CHPs, gas fired generators, compressor stations, or ICT). Such research will provide technical and functional specifications for the modelling, simulation and optimisation of energy network infrastructure at different scales, and identify the future needs for energy networks.

2) ***Risk assessment of integrated energy infrastructure***. The complex interdependencies and interactions between various energy systems may increase the risk of cascading failure of the integrated infrastructure. New methodology and assessment tools are being developed to better understand and quantify the risk of cascading failures. The probability of failures in the integrated energy system needs to be quantified, and the potential for cascading, parallel and escalating failures be investigated. The key vulnerabilities in the integrated energy networks should be identified. Investigation needs to be carried out to study how the integrated networks should be modified to reduce vulnerability and improve resilience. Here the candidate solutions could be those based on implementation of graph theory [31]-[34].

3) ***Optimal operation of integrated energy network infrastructure***. Integrated energy network infrastructure with a high penetration of distributed energy resources, will involve multiple entities, and there are major challenges on how to co-ordinate and harmonise many types of control actions in an integrated energy network infrastructure considering such multi-entity involvement (e.g. Network Operators, DER owners, suppliers, aggregators, and various types of energy service companies). There is much research looking at methods for optimal operation of integrated energy infrastructure. There are also many emerging technologies. For example, Distributed Ledger Technology (DLT, e.g. Blockchain) has been recently recognised as a revolutionary technology that provides an effective and reliable means of co-ordinating and harmonising such activities across multiple interested entities. DLT-enabled optimal operation strategies could be used for the integrated energy network infrastructure based on heterogeneous ICT infrastructure and data availability.

4) ***Expansion planning of cross-national gas and electricity networks under uncertainties***. Using the European energy system as an example, uncertainties in European energy systems result in difficulties in making an optimal investment decisions on pan-European gas and electricity networks. Stochastic models for expansion planning of combined pan-European gas and electricity networks need to be developed to determine the optimal expansion of both networks. The key uncertainties considered should include connection of renewable electricity generation and distributed gas injection (e.g. Power to Gas and shale gas), development of gas interconnectors and gas storage facilities, development of electricity Super Grid, energy price and energy demand.

5) ***Whole-System Modelling***. Whole-system modelling is a promising way to obtain essential quantitative insights into the challenges of decarbonisation, energy security, energy equity, and cost-effectiveness. Current work mainly focuses on energy studies within energy, environment and economy domains. Modelling of integrated energy networks provides a platform that assists detailed whole-system modelling for technical and socio-economic analysis at different scales (from generation, transmission, distribution down to demand behaviour) and at different time periods, which provides finer granularity regarding detailed energy flows on the networks considering various technical constraints rather than merely energy balance at the system level.

6) ***Analytical Support for New Security, Quality and Design Standards***. The current security, quality and design standards were not designed for future low carbon integrated energy networks, and are becoming barriers for further development of smart energy systems. Integrated modelling of energy systems enables analytical support for new security, quality

and design standards. Novel methodologies and approaches need to be investigated to link integrated modelling with development of new security, quality and design standards.

7) ***Investigation of business cases, market design and regulatory frameworks for integrated energy systems***. Current business models, market designs and regulatory frameworks cannot provide adequate incentives for the players to move towards low-carbon, low-cost, high-efficiency and smart energy systems. Considering the large number of potential actors, physical systems, market constraints and the multi-objectives, the design and operation of new business models, new markets and new regulatory frameworks with increasing interdependencies, interactions and data requirements within the integrated energy systems are urgently needed.

4. ICT AND DATA ANALYTICS FOR FLEXIBLE AND RESILIENT MULTI-VECTOR ENERGY NETWORKS

The Information and Communication Technologies (ICT) are recognized to have their own role in pursuing sustainable development goals defined by United Nations 2030 Development Agenda [35]. To ensure optimal operation and a high level of flexibility of future multi-vector energy networks, implementation of adequate novel technologies will be one of its enablers, jointly with new concepts and algorithms. It is expected that concepts based on large quantities of data will particularly contribute to this agenda and furthermore will open doors for fostering overall system resilience, both from its quantification and real-time monitoring, as well as generating control measures for its support. It is also expected that new, data-driven and model-free approaches will enable another level of flexibility and optimal system operation by processing data obtained from the primary assets, monitoring the system operating point without knowing its model, parameters, structure, or state. On the other hand, big data acquisitions, transmissions, storage and analytics require data centers with huge computing power, giving a rise to more consumptions of energy [36]. This has already raised concerns and different methods are proposed in the literature toward greening big data [37], [38]. Still, there is a room opened for discussions how multi-vector energy networks can contribute to meet big data green challenges.

In this section, aspects related to integration of large quantity of data over ICT and customized data-acquisition platforms will be discussed. An example of a Flexible ICT Platform (FICTP), with an integrated situational awareness tool, designed for multi-vector energy network Big Data processing will be described and discussed. In the context of the potential future scenarios and network changes, discussion about their impact to both the platform and the tool is given.

4.1. ICT, Big Data and Data Analytics

An integrated multi-vector energy network infrastructure will continuously generate data with large **v**olume, high **v**elocity and diverse **v**ariety and **v**eracity (4V). It is not fully clear what is the exact meaning of the term "*big data*", because in different disciplines, or physical processes, it is relative which problem can be considered as a *big-data problem*. However, these are *data analytics* approaches for dealing with big-data problems. The definition of *big data* depends on whether the data can be processed and examined in a time that meets a particular application’s requirements. For one company or system, big data may be 50 TB; for another, it may be 10 PB [39]. In this context, quite intuitively, one can accept that in the field of multi-vector energy networks, big data may refer to the processing of Gigabyte, Terabyte or even larger quantities of data, with the data likely to have very different origins (e.g. voltage, or current phasors, temperatures from different locations in the heat network, or gas pressure at the customer terminal). Such a variety is one of the challenges which must be adequately considered when creating applications in which different energy sectors are simultaneously considered; for example, state estimation/dynamic state estimation of an integrated MVENs [40]-[42].

The term *velocity* is used here to describe the frequency of incoming data that needs to be processed. This frequency must be high enough, so that the fastest transient processes occurring in the physical system can be monitored. *Veracity* is concerned with the accuracy of data obtained from the asset.

There is a need for new big data (data analytics) solutions suitable for the whole energy system with analysis of a) offline data sets for planning, as well as b) real time data analysis for control (identified today as priority by the Industrial community). A greater understanding of the quality, robustness, architecture and cyber security of the applied ICT network [43]-[45], as well as approaches for data driven applications, could significantly contribute to multi-vector energy network characterisation, resilience and flexibility. Finally, there is also a need for practical demonstration and validation of approaches for integration of data from different energy networks and their usage in specific applications.

4.2. Flexible ICT Platform for Big Data and Multi-Vector Energy Networks Situational Awareness

Assessment of multi-vector energy network 4Vs data sources and the case for their integration can be undertaken to provide a starting point for creating requirements for design of a FICTP for Big Data processing. For this purpose, a detailed understanding of the data origin, nature, range, dynamic properties and interactions, is of critical importance and should be resolved at the network modelling and simulation phase of the design of a FICTP.

Major sources of uncertainties, including the entire measurement chain and the ICT network, are equally important and can be obtained by understanding the end to end data acquisition chain, starting from sensors installed at the asset level, communication infrastructure transferring measured data to the data acquisition platform, or different technologies supporting the entire process, e.g. time synchronization. Uncertainties are also related to the quality of modelling of the primary asset and they must also be considered.

The major candidate FICTP building blocks can e.g. include PI-servers, and/or the Apache Hadoop big data Java tool. Appropriate big data pre-processing techniques can be used to improve the data quality, especially in a highly uncertain environment with corrupted data sets.

4.3. Situational Awareness of Multi-Vector Energy Networks

Situational awareness is the first aspect needed for successful monitoring and *open loop control* of multi-vector energy networks, including design of early warning systems. Here the term “open loop control” means derivation of recommendations which control measures should be applied. They are a typical decision support tool, providing real-time instructions to operators, who would undertake the actual control measure and by this *close the loop*. This kind of control is suitable for processes described with time constants long enough to allow a human intervention and system support in terms of its regulation. A move towards *closed loop control* requires reliable ICT and robust concepts. For example, frequency control in electricity networks, supported by heat and gas networks through flexible interface technologies, e.g. Combined Heat and Pump (CHP).

By designing a multi-vector energy networks situational awareness tool (M-SAT) a secure whole-system operation considering different types of system constraints can be supported. It traditionally relies on the known MVENs topology and state. These are a prerequisite for superimposed applications, allowing e.g. a more flexible system operation and control, or monitoring of the network resilience level. The M-SAT can combine data obtained over ICT networks from different energy networks, which can be considered as one of the key features enabling flexibility and resilience capabilities.

The M-SAT, integrated into the abovementioned FICTP, can rely on e.g. robust linear/nonlinear dynamic recursive state estimators considering the known nature of random processes characterizing the entire metering chain [46]-[50]. For example, traditionally used a) least error squares, or b) weighted least error squares estimators can be implemented under the assumption that the stochastic nature of the process and measurement noise is considered to be a non-correlated white noise. When the stochastic nature is known, Kalman-type estimators can be used, e.g. Kalman Filter, Extended Kalman Filter, or Unscented Kalman Filter. Knowledge extraction approaches can also be based on classical Digital Signal Processing (DSP) approaches, including Discrete Fourier Transforms and its variants like Fast Fourier Transform, or Short-term Fourier Transform. When dealing with detection problems, Wavelet Transform can be used, whereas Stockwell Transform has been found to be particularly applicable for design of novel algorithms processing complex signals typical for transient processes. Stockwell transform is a generalization of the short-time Fourier transform, extending the continuous wavelet transform and overcoming some of its disadvantages.

State estimator can be considered as one of key situational awareness applications, enabling nowadays optimal functioning of power system control centres. Extension of the estimator to e.g. heat and gas networks can open doors for new applications, supporting flexible operation of a multi-vector energy network, characterized with a high level of resilience. Having a reliable network/system state, advanced application, e.g. security/stability monitoring, or resilience quantification, can be realized.

According to the above discussion, M-SAT can consider security limits from multi-vector energy networks and derive new security indices based on the whole-system approach. Such a tool can be developed so that it can be adapted to consider different types of future challenges, e.g. the impact of future technology, or concepts for future advanced control, both centralised and decentralised.

In Figure 4.1 a global block diagram of the FICTP, with the integrated M-SAT tool is presented. Different types of sensors, used for different purposes, are detecting, or measuring various physical properties in the multi-vector energy network. For example, statuses of power system circuit breakers, or voltages, currents, active and reactive powers and frequency are obtained from a power system. Over communication infrastructure, these data are further transferred to the Data Integration block. Communication infrastructure has to provide a secure and fast data transfer according to one of accepted/agreed/prescribed communication protocols. Data from other sources, e.g. meteorological, or society data are assumed to be available to support different types of Applications, which are a part of the Data Analytics block. Dependent on the complexity of application, different data analytics are applied, but the key point is that it is expected that the quantity of data is expected to be large, so that efficient approaches for knowledge extraction have to be implemented. Information extracted is intended to be used to support visualisation, policy, market, control and other serviced relevant for the network.

The role of novel sensor and ICT technology will be even more critical when it comes to control, or protection aspects of MVENs. Here the importance of understanding the sources of uncertainties, as well as risks related to them, will be essential (see Section 7).

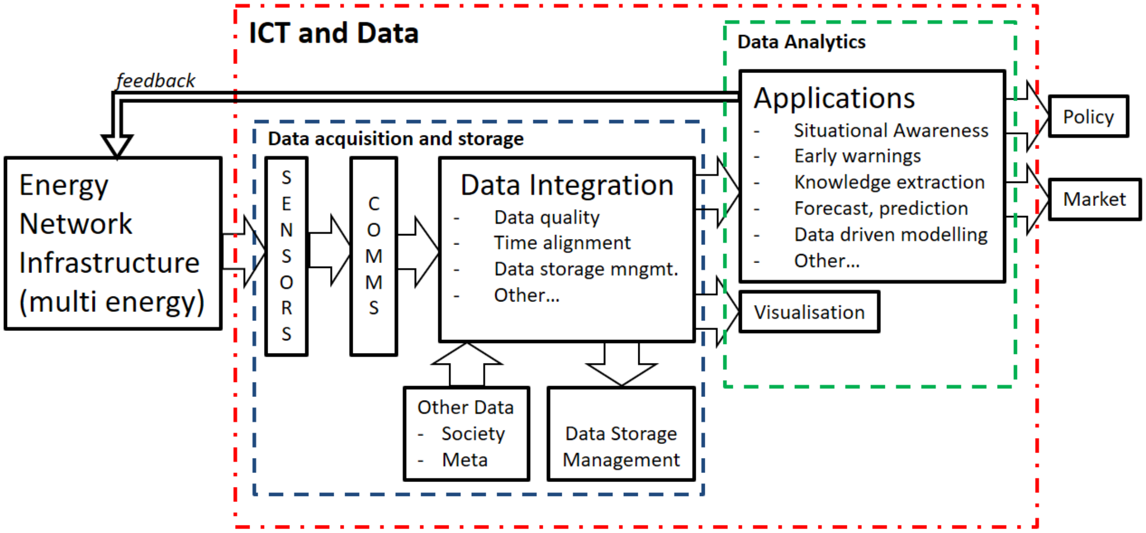

Fig. 4.1 Block diagram of the FICTP with an integrated M-SAT tool based on Data Analytics

5. POLICY AND SOCIETY

As described in the introduction, energy systems in many countries are undergoing profound changes in the way that energy is generated, distributed and used. In terms of distribution, energy networks are facing significant changes to meet the challenges of facilitating decarbonisation, while maintaining energy security and protecting consumers. Planning, designing, operating and regulating networks will all be affected by these changes. For example, the transition to low carbon energy requires rapid development of renewable energy in both national and local energy systems and this results in increased demand in flexibility which does not fit the current strict dispatch and planning rules of the electricity network [51]. Generally, the current energy systems (electricity, heat, gas) are planned and operated separately, but greater interdependence between vectors in terms of the use of gas to generate electricity, or the use of electricity to provide heat, means that a new perspective involving a MVENs approach may bring significant benefits.

For instance, in terms of economies of scope, [52] suggests that industries could reap benefits in scope by jointly managing knowledge related to regulation, environment, planning, and policy development. A MVENs approach can facilitate the development of multi-vector energy technologies and their interactions to bring about minimisation of system cost and maximisation of environmental performance [6]. In Europe, cross-vector integration is seen to have a significant potential for promoting system flexibility and security of energy supply, while end-use sector coupling can increase the scope for harnessing intermittent renewable energy sources [53]. Options that are enhancing flexibility in Denmark, for example, have been highlighted by [54]. These include flexibility from interconnectors, conventional power plant flexibility, flexibility from heat sector integration and flexibility from the gas and power sectors. One thing that is clear is that interest is mounting in a number of European countries (including Finland, Denmark, Germany, Netherlands and the UK) regarding cross-vector integration options and this has led to an increasing number of modelling and simulation studies [55], [56].

This brings into focus the question of the role of policy in facilitating MVENs. Many actors in the energy sector are looking for a clear steer from government policy as to the direction and speed that the energy transition should take. The need for a relatively stable and clear policy environment is particularly important for energy networks, which are characterized by multiple organisations with high, long-term, financial and non-financial commitments [57]. In the UK and many other jurisdictions, the main driver for the transition in the energy sector has been climate policy, but uncertainties remain both because of a lack of clear policy direction in some areas and the competing interests of different sectors within the energy industry [58]. Energy networks are at the heart of some of these uncertainties and the nature of the challenge will vary between networks. For example, a key challenge for the electricity network is the need to meet the increased demand that will arise from using electricity to help decarbonize heating and transport, while at the same time incorporating greater renewable generation embedded in the distribution network [59]. In contrast, the very future of the existing gas networks is uncertain, and while it is clear that a substantially decarbonized energy system will have to reduce its reliance on natural gas, it is very unclear whether and to what extent the current network might be repurposed to distribute hydrogen instead [60].

With the rapid nature of changes occurring in energy networks, there is a need for a clear sense of direction from government policy, while also maintaining flexibility to deal with unexpected future requirements and challenges. Experts anticipate an energy system that will have a combination of incremental and radical changes with many trials of technology, regulation and policy measures [61]. What this means is that each of these components must be flexible and adaptive to accommodate learning as the results of the trials become known and the nature of the challenges become clearer.

Therefore, like any other transition pathway, a MVENs approach will require a deliberate policy package. Any policy package will need to take account of both the existing energy landscape and also the overarching goals of energy policy in a particular country. An international review of existing energy transition policies will be a strong reference point to begin with. There may also be lessons that can be drawn from transitions in other fields but energy networks also have characteristics that make them rather unique [62]. Potential evolutions of the system need to be studied to pre-empt future challenges and increase certainty in the responses required to ensure a transition that is cost-effective, inclusive and socially acceptable. This implies that while technological solutions are core to any transition, these need to be considered alongside the economic and societal implications. Policy will only be effective to the extent that it can drive the behaviour of investors and consumers. Thus, engaging with all stakeholders will help shape policy that is more inclusive while understanding the political economy elements considering that most reforms come with "*losers and winners*" [63], [64]. Clearly, the dynamic and uncertain nature of the transition as well as its strict time constraint do not allow policy to be designed, implemented and monitored as has been done in the past. New approaches are being reported in the literature that enable policies that are dynamic, interactive and adaptive [65]-[68] and these should be explored and tailored to be appropriate for the specificities of MVENs. In MVENs, there are interactions of systems but also institutions and may require new mechanisms and organisations for coordination. In addition, consumer awareness, intentions to adopt, acceptability and behavioural patterns will all be relevant in designing a policy that is dynamic, adaptive, interdisciplinary and one that deals with the energy trilemma (3Es) in an integrative and an interactive way [62].

Given the above, the following investigations (see Figure 5.1) can inform the policy design, implementation and control phases of the transition in general but more specifically the MENs pathway:

1) ***Evidence from local and international experience***. Using both local and international experience to gather evidence on the energy transition, network challenges, regulation and policy evolution as well as documenting and analysing examples of MVENs.

2) ***Stakeholder views on MVENs [Qualitative research]***. Engaging the wider energy community and experts on various pathways and in particular different configurations of MVENs to enable investigations into its potential, its benefits and challenges, political economy, as well as the suitability of existing policy and regulatory framework to accommodate and promote a MVENs and any other changes that it comes with.

3) ***Societal impact and consumer behaviour***. Analysis of societal impact and consumer behaviour are essential components of the MVENs. Investigating consumer awareness, intentions, potential impact of MVENs and expected behavioural changes can help shape decisions in network operations, policymaking, regulation and investments. The same is required to investigate the implications for the cost of energy, energy poverty, energy democracy and other regional and societal inequalities of the possible pathways and network architectures (transnational, regional and hybrid system mentioned in the modelling and architecture section).

4) ***Outputs of the above investigations are potential inputs for designing policies for the various MVENs systems***. A policy package that is dynamic and adaptive can then be designed using insights from the dynamic adaptive policy pathways framework and other relevant models that are tested and trialled in both energy and non-energy fields.

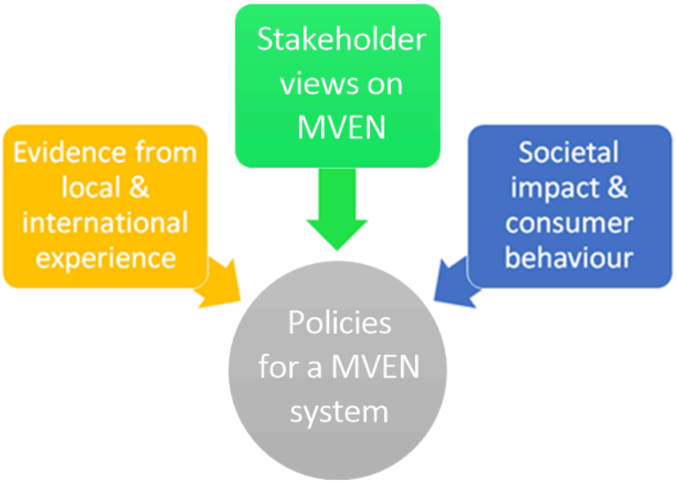

Fig. 5.1 Areas of research to inform the development of policies for a multi-vector energy network

6. MARKETS AND REGULATION

Historically, markets and regulatory frameworks for MVEN were developed for a centralised supply system with large-scale energy resources and passive energy customers, reflecting the technical control, operation and investment of energy systems. Decarbonisation, digitalisation and decentralisation are fundamentally changing the energy landscape, where energy resources are increasingly diversified and decentralised, and flexibilities are spreading across heat, power, and transport sectors. This move is changing the way energy is produced, transported, and consumed. The market and regulatory arrangements have to step up to the change and support the transition towards a smart, flexible, decentralised energy system. The arrangements should reflect a very different network users, network operation and development, and open up new market routines to work with decentralised and diverse energy technologies, new energy players, disruptive business models, and smart energy customers.

An enduring set of commercial and regulatory solutions would help to shape intelligent, efficient, adaptive and lower carbon MVENs within which both existing and new energy players would profit. The low carbon transition not only increases the complexity, interdependency and uncertainty of future MVENs [69]-[71], it also exacerbates some of the existing challenges, examples of electricity network challenges include, voltage and frequency stability, fault current and three-phase imbalance [72]-[76]. Furthermore, they will disproportionately impact on different types of customers, such as domestic, commercial and industrial, and different areas of networks, such as urban, rural areas [77]. This makes it extremely challenging to understand and translate the needs of MVENs to wider market participants. On the other hand, there are disruptive alternatives to address network issues from regulation to commercial arrangements for the network and customers, such as high-level network regulation recommendations on the distribution network in the context of a possible increased connection of distributed energy resources [78], to the new business model for distribution network to make use of the spare and back up network capacities [79] and increased network operational intelligence to manage congestions and constraints [80]-[83], and non-network solutions to tap into customers' energy resources [84], [85]. This requires novel approaches to approximate the increasingly complex and flexible energy systems, able to effectively and efficiently represent the complicated and interconnected network problem, and reflect the large volume of new network and non-network solutions from the current and future market participants.

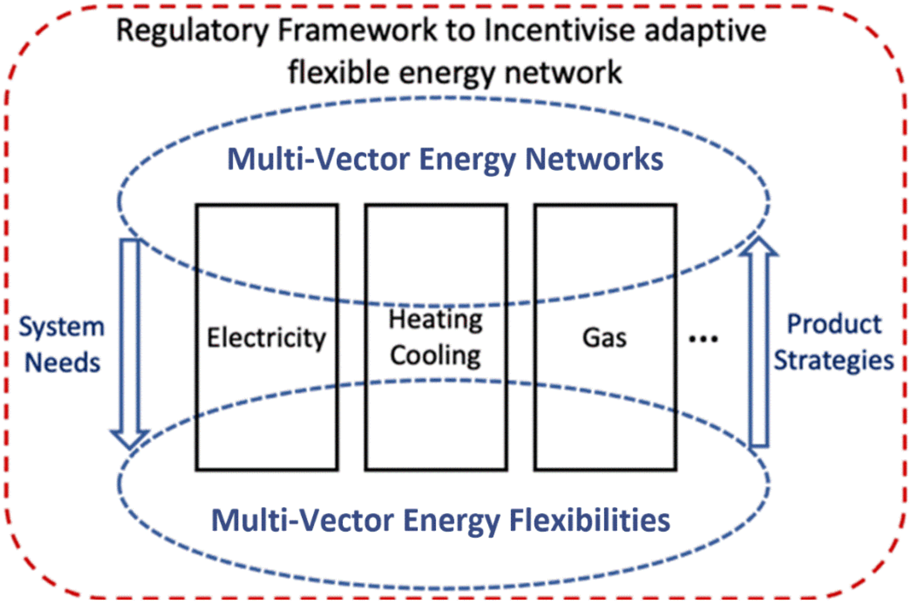

Fig. 6.1 Logical framework for designing enduring market and regulation solutions

6.1. Development of holistic techno-economic tools for commercial arrangements and regulatory frameworks

Existing techno-economic algorithms and tools are facing the challenges of increased system complexity, nonlinearity and uncertainty, which make it difficult for scalable design. The existing simplification, linearisation and decomposition methods to scale the modelling and analyses are mainly focused on the optimisation formulations and manipulations of existing solvers [86]-[88]. Instead of placing all the burdens on the optimisation, a fundamental redesign is considered for network access, balancing markets and services, regulatory arrangements by identifying the dominant factors and dynamic interactions between differing network functions and across different energy vectors for model reduction, simplification and connections. From the deep insights into systems and customers, fundamental new ways to represent the system needs and solution offers across multiple energy sectors will be developed to achieve the right balance between computational requirements and accuracy for the integration of the MVEN.

For differing commercial/regulatory purposes, the dominant factors and dynamic interactions are different. The system decomposition, the process of breaking a problem down into individual, tractable and manageable sub-problems, is thus not unique. The nature of the network, the degree of integration and flexibility, the extent of ICT infrastructure, and societal and policy should be considered as well. The existing commercial and regulatory arrangements presently limit a level-playing field between centralised and decentralised systems, between incumbents and new players, there needs to be more open and inclusive arrangements to maximise energy resources across the whole system [89]-[91].

6.2 Commercial and regulatory innovations for promoting whole-system efficiency, resilience and integration

To promote whole-system efficiency, resilience, and integration, the market framework for multi-vector energy networks should be able to translate the system needs into simple, efficient, and integrated commercial signals that will open up new commercial routes for a wide range of technologies and energy players without compromising the supply security. The regulatory framework for multi-vector energy networks should be able to combine the characteristics of different energy vectors to provide incentives that can exploit flexibilities and their complementarities across multiple energy vectors and address the network problems in an integrated way to maximise the overall system efficiency.

It is critically important that innovations in the market and regulatory frameworks can withstand the test of systems at different scales, from highly connected national and Pan-European mega systems to community / service based supply system. The innovation will incorporate new technologies, flexibility, business models, society, and policy options. Crucially, the innovation will have a greater role to play to extract additional value from existing network infrastructure, such as shared network access with a third party network operator to mobilise network spare capacity [79].

6.3 Future-proof commercial and regulatory frameworks for major challenges

Decarbonisation and Covid-19 have demonstrated that our energy landscape and consumer energy behaviour could change dramatically in a relatively short period of time [92], commercial/regulatory innovations thus have to withstand major societal, technical and environmental challenges. This requires not only increased flexibility in energy networks and energy customers, crucially, flexibility in commercial and regulatory arrangements that enable and reward adaptable and resilient energy networks to facilitate the long-term sustainability, efficiency and adaptability of our energy supplies.

7. RISK AND UNCERTAINTY

MVENs consist of huge numbers of active system components with distinct characteristics, regulated by vast numbers of controllers, connected through highly reconfigurable networks. The network planning and operation is further complicated by the growing number of uncertainties as a result of the deregulated market structure, intermittent renewables (e.g. wind and photovoltaic farms) and novel loads introduced by the electrification of heat and transport. However, techniques to analyse uncertainties within interdependent physical and cyber networks are still in their infancy and are yet to be thoroughly applied to MVENs. Moreover, due to the growing interdependency between energy vectors and the impact of any one energy vector on the capability of another (e.g. the impact of high penetration of wind generation in electricity network on the gas network as demonstrated in [93]), a better understanding of risk and uncertainty propagation in MVENs is required [94].

This needs to build on prior expertise [95] to develop the new techniques needed to adequately model and analyse the impact of the various sources of uncertainty in energy networks. The resulting risks within these interdependent MVENs should then be quantified so that new opportunities for mitigation can be exploited.

With regards to risk and uncertainty in MVENs, the following challenges have been identified for further investigation:

7.1. Uncertainty propagation through interdependent MVENs

Due to the interconnected and interdependent nature of MVENs, the uncertainties from one network can propagate to the other, resulting in unfamiliar risks to the security of energy supply. It is therefore important to quantify the uncertainty propagation in MVENs by advancing promising single-vector techniques for uncertainty analysis such as the Morris Method and Sobol measures [95]. These techniques can be validated in simplified MVEN models (discussed in Section 3) for initial development before application on larger and more complex realistic systems.

7.2. Uncertainty quantification on variable timescales and locations

There is a need to quantify the stochastic dependence present on different temporal and geographic scales between the various uncertainty parameters in MVENs. These quantifications can be derived as analytical expressions (e.g. as discussed in [96]) that can then be integrated into suitable market development strategies (discussed in Section 6). In addition, these quantifications can feed into the prospective network approaches discussed in Section 2, not only on operational aspects, but also on delivering flexible multi-vector planning decisions under uncertainty.

7.3. Impact of critical uncertainties

To address the needs of bulk transnational energy transmission networks (A1), suitable sensitivity analysis methods (e.g., Morris, Sobol, Peasron correlation, Borgonovo) [97], in addition to data availability and analytics (as discussed in Section 3 and Section 4) can be employed to identify critical uncertainties influencing the operation of bulk energy networks. The critical uncertainties in the energy network can be broadly classified into:

- operational variables [98] that represent the variation in system quantities during normal operation such as electricity/gas demand fluctuations, wind/photovoltaic power fluctuations and gas supply uncertainties;
- disturbance variables [98] that represent unexpected events which move the system into emergency operating states such as electricity transmission line outages, generation capacity outages, gas import pipeline outages, gas terminal outages and gas storage facility outages [99].

This can result in the development of novel techniques for identifying critical monitoring points helping to reduce data uncertainty and the possible impacts of corrupted data streams on MVENs situational awareness.

7.4. Metrics for communicating uncertainty and risk

More often than not, risk and uncertainty can be neglected as well as poorly communicated to the energy network stakeholders. Risk metrics are often used to assess and communicate the security of supply in the energy networks, e.g., the common risk metrics for electricity networks are loss of load expectation (LOLE) [100], expected energy unserved (EEU) [100], capacity margin, average circuit unreliability [101], average electricity customer interruptions [102] and average minutes lost per customer [102], whereas the primary risk metric for gas networks is 1 in 20 peak day [103]. However, metrics to communicate risk in MVENs are yet to be thoroughly developed; therefore, it is important to investigate suitable risk and uncertainty metrics in consultation with the concerned stakeholders. The development and evaluation of multi-vector risk metrics would enable decision-making for policy makers and system operators on optimal investments (e.g., gas vs. electricity) and offer awareness on evolving security and reliability problems [99] (e.g. impacts of heat decarbonisation on MVENs).

One way of achieving this is to conduct interviews (as described in Section 5) including questions with respect to the communication of uncertainty and risk. To facilitate this consultation, an introductory guide to risk and uncertainty can be produced to provide a common accessible set of metrics enabling greater engagement of the wider community.

7.5. Generalised risk methodology for future challenge assessment

The outputs from Sections 7.1 – 7.4 can be combined to form a general risk assessment methodology that can be used to assess the impact of possible external shocks on energy networks (see Figure 7.1). This can build on previous single-vector driven approaches such as the GARPUR project [104] to produce a clear methodology with robust output metrics. The development of this stakeholder-driven generalised risk quantification framework can then be used to address the MVENs challenges (discussed in Section 2) and can be shared with the wider research community to encourage further development of advanced intelligent and autonomous control-based risk mitigation solutions. This can become the groundwork on which to develop future security assessment of interdependent critical infrastructure systems.

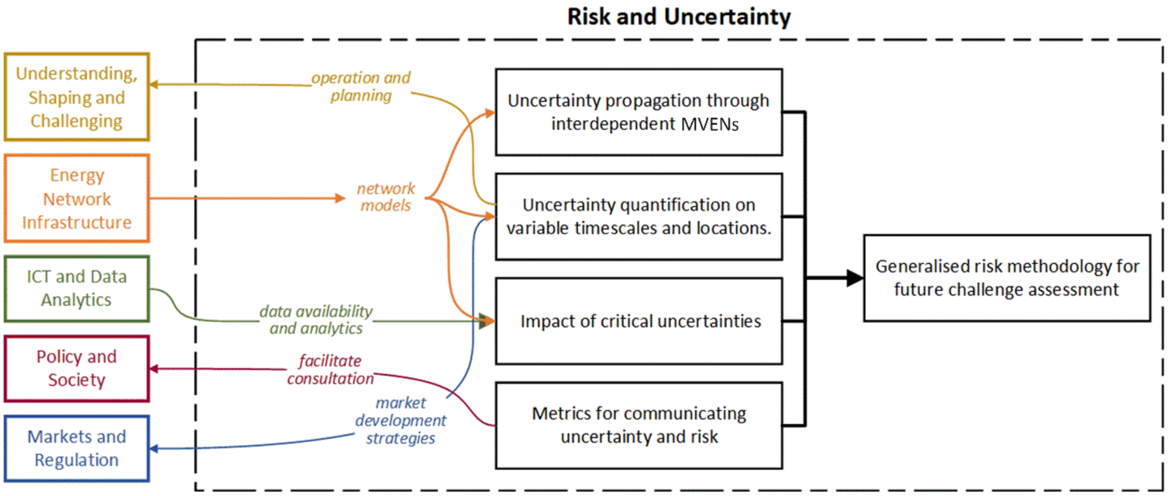

Fig. 7.1 Block Diagram illustrating the development of risk and uncertainty methodology

8. CONCLUSION

Optimal utilization of primary energy relies on a deep interdisciplinary understanding of multi-vector energy networks (MVENs), plants, physical infrastructure, sources and nature of uncertainties, Information and Communication Technologies (ICT) requirements, cyber security, big data analytics, innovative business models and markets, policy and societal changes. This paper proposes and applies an interdisciplinary perspective to investigate future energy network architectures. Early results consider the potential role of interconnectors in a possible future bulk transnational energy transmission network, given the planned doubling of interconnector capacity. Regarding a more regional and service-based network, the research has investigated the impact of rapid electrification of heat demand in the distribution networks. The challenge of societal shifts, such as greater home-working, has also been investigated, and initial work shows significant change in the UK electricity demand during the COVID-19 lockdown in early 2020. Furthermore, the approaches for design, planning and operation of energy infrastructure are undergoing a transformation to meet the challenges of energy trilemma, especially decarbonisation. It is important to adopt an interdisciplinary perspective to analyse the complex technical and economic interactions and interdependencies between different energy carrier systems, such as electricity, natural gas and hydrogen, and to quantify, illustrate and make appropriate use of the synergies between them. Equally, efficient management of data from energy networks is recognized as a particular challenge. In the paper, an example of a Flexible ICT Platform, with an integrated situational awareness tool, designed for multi-vector energy network Big Data processing is proposed and discussed. The importance and ways of efficient handling of large quantities of data are shown. The logic needed for supporting visualisation, policy, market, control and other services relevant for MVENs is presented and discussed. Next, it is vital that Government policy provides a clear sense of direction to the energy sector, including the expected role for MVENs, so that the needs of society can be met appropriately. Well-designed policy can incentivise innovation, while removing barriers to a interdisciplinary MVENs approach and help to co-ordinate the competing interests of different actors in the energy system. However, any policy approach will also need to be flexible enough to deal with unexpected future requirements and challenges as they arise. At the same time, an enduring market and regulation framework can provide the right incentives to shape intelligent, efficient, adaptive and lower carbon MVENs. Ideally, this is achieved by meeting the MVENs needs with the diversified offers provided from multi-vector energy flexibilities. For that purpose, an interdisciplinary and coordinated approach is required to better plan and operate the MVENs while ensuring options are open to accommodate potentially very different future technologies and business models. Finally, the network planning and operation of MVENs faces a growing number of uncertainties such as energy policy, market deregulation, intermittent renewables and new loads. This, along with the growing interdependency between energy vectors, necessitates a better understanding of risk and uncertainty in MVENs. This paper discusses the need to develop novel techniques for adequate modelling and analysis of the impact of various sources of uncertainty in MVENs, quantify resulting risks and exploit new opportunities for mitigation. A general risk assessment methodology can then be designed to address the challenges and can be shared with the wider research community to encourage progress of advanced intelligent and autonomous control-based risk mitigation solutions. This can become the foundation on which to cultivate future security assessment of interdependent critical infrastructure systems. Authors of the paper plan to move forward in this direction and to present more detailed results in the next stage of the research.

ACKNOWLEDGMENT

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