Environment, Development and Sustainability
https://doi.org/10.1007/s10668-024-04664-9

Responding to the UN sustainability goals in transdisciplinary partnership through network action learning

Katrin Dreyer-Gibney[1] · Paul Coughlan[1] · David Coghlan[1] · Szu-Hsin Wu[2] · Aisha Bello-Dambatta[3] · Richard Dallison[3] · Aonghus McNabola[4] · Daniele Novara[4] · Annum Rafique[5] · Isabel Schestak[3] · Jan Spriet[6] · Nathan Walker[3] · Prysor Williams[3]

Received: 30 August 2023 / Accepted: 18 February 2024

Abstract
The global water crisis, an enormous concern according to the World Economic Forum, poses a significant challenge to long-term sustainability, exacerbated by the high energy demand associated with water supply and treatment. As the renewable energy sector grows, the need for green technologies to support the water-energy nexus becomes evident. However, mere technological advancements are insufficient to address complex water-related challenges. This paper presents a transdisciplinary collaborative effort involving engineers, geographers, management researchers, and environmentalists working with practitioners in a cross-border network. The study explores through action learning research how, in a transdisciplinary partnership, network action learning influences the exploration and implementation of novel green technology and the development of innovation capabilities. The research is structured around three themes: green technology platforms, policy support and guidance, and dissemination and collaboration. It identifies the factors impacting technology exploration and application and how concurrently green innovation capabilities are developed. The study emphasizes the significance of transdisciplinary collaboration and offers valuable insights into addressing UN Sustainability Goals related to clean water, sustainable industry, and partnerships. It contributes to innovation capability theory and provides practical guidance to researchers, practitioners, and policymakers, emphasizing the need for holistic approaches to address the water-energy crisis and achieve sustainable development.

Keywords Green innovation · Innovation capabilities · Transdisciplinary partnership · Water-energy crisis · Action learning research · Network action learning

1 Introduction

Despite the World Economic Forum's acknowledgment of the water crisis in its global risk report, the water sector lags behind other industries in innovation, posing a challenge to long-term sustainability due to its high energy demand (Wehn & Montalvo,

Extended author information available on the last page of the article

Published online: 20 March 2024

2017; Koop & van Leeuwen, 2017; Ali et al., 2023). While there is a growing demand for green technologies in the water-energy nexus, merely focusing on their development and funding proves insufficient. Research alone cannot resolve complex issues; obstacles hinder the application of findings in practice, such as the lack of guidance for researchers and institutional pressures prioritizing publication over tangible contributions to society.

Furthermore, the UN Sustainable Development Goals (SDGs), urge society to form new partnerships for the sustainable management of communities, resources, and the planet. This monumental challenge necessitates an integrated approach that combines research and practical application, as highlighted by Revans (1998), distinguishing it as a *problem* rather than a *puzzle*. *Puzzles* have definitive solutions that can be solved by specialists and experts, whereas *problems* lack a single, straightforward solution. *Problems* are conducive to action learning, where individuals from diverse backgrounds can propose different actions based on their own values, experiences, and intentions.

In response to the SDGs, we explore a specific approach—network action learning (NAL). NAL focuses on action learning within a network, addressing *problems* that require a transdisciplinary approach (Coughlan & Coghlan, 2011). Aligned with the call for transdisciplinary collaboration, Agramont et al. (2019) advocate for collaborative research, stressing the importance of integrating different disciplines and stakeholders to generate actionable knowledge. This assertion is echoed by Moallemi et al. (2020), advocating for co-learning to enhance "genuine stakeholder engagement". Similarly, Snyder and Wenger (2010) underscore the role of communities of practice in bridging organizational boundaries and enhancing collective knowledge. Additionally, Barth et al. (2023) emphasize the potential of social units in achieving sustainability outcomes.

Our focus is on developing and implementing novel green technology to reduce the carbon footprint associated with water distribution. It involves 13 researchers working with practitioners in the water sector to reduce the energy burden linked to water distribution. Engineers, geographers, and environmentalists apply scientific expertise, while management and action researchers facilitate action learning through critical reflection. As advocated by D'Amore et al. (2022) in a study concerning the water-energy-food nexus, we aim to bridge the gap between research, practice, and policymaking, applying knowledge exchange and continuous collaboration.

This paper shares our experiences and reflections during the development and implementation of green technology and practices to address the water-energy crisis, contributing to the development of innovation capabilities. The research questions guiding this paper are: How can a transdisciplinary partnership through network action learning impact the development and implementation of green technology and practices? Additionally, how does this approach contribute to the concurrent development of capabilities for green innovation?

This study aims to offer insights into achieving UN Sustainability Goals, contribute to innovation capability theory (Börjesson et al., 2014; Teece, 2019), and provide practical guidance for researchers, practitioners, and policymakers. The emphasis is on taking a holistic approach to address the water-energy crisis and achieve sustainable development.

The subsequent sections provide an overview of the theoretical underpinnings of innovation capability, an introduction to the theory and practice of action learning, and details of the research methodology, action learning research (ALR). ALR is an approach that combines scholarly inquiry with practical application, fostering collaborative problem-solving and continuous learning to address real-life problems. Thereafter, examples of practical challenges faced by our network in addressing water-energy related issues, contributing to several SDGs, are presented. The paper concludes by articulating our contributions to theory and practice and our alignment with the UN Sustainability Goals.

2 Theoretical background

Addressing the complex challenges posed by the United Nations Sustainability Goals, current research has increasingly turned to innovative methodologies and learning frameworks (e.g., Agramont et al., 2019; Aguiñaga et al., 2018; Barth et al., 2023; Schouten et al., 2021; Zarei Mohammad et al., 2019). This literature review critically examines the intersection of network action learning (NAL) with the development and implementation of novel technology in the context of advancing sustainable development.

Our first research question investigates ways in which network partners can influence through the application of NAL the development and implementation of novel green technologies and practices in response to the UN Sustainability Goals. The second question explores the role of network action learning in developing innovation capability. Therefore, we investigate further what is known about the concepts of innovation capability, learning mechanisms and action learning.

2.1 Innovation capability

The notion of innovation capability derived from organizational capability development theory (Börjesson et al., 2014; Teece, 2019). In Table 1, we categorize practices and actions that, based on existing knowledge, constitute innovation capabilities. These practices and actions include those that link knowledge, technology, and resources; enable learning from experience and with others; and facilitate the transfer of learned insights to other initiatives.

Within the medical technology industry in Sweden, Olsson et al. (2010) underscore collaboration with partners and the ability to learn in a network. Lin et al. (2013) emphasize the role of learning capability as an enabler for innovation ambidexterity in Taiwanese-owned strategic business units from various industries. Examining manufacturers across 22 countries, Sousa and da Silveira (2017) stress the joint design of services and products, emphasizing the importance of learning from customers. Focusing on innovation projects for social and environmental sustainability in multinational manufacturers, Behnam et al. (2018) highlight the significance of learning from and with external actors in sustainability projects. In Nordic manufacturing companies, Pieroni et al. (2021) use action research to link sustainability business models with business processes, fostering circular economy business model innovation. Exploring water system transition in Oklahoma, USA, Hartman et al. (2017) find a significant relationship between innovations and dynamic capabilities, particularly in reconfiguring existing knowledge, technology, and resources. In the electronics industry in Taiwan, Lin and Chen (2017) highlight company abilities to combine, apply, assimilate, and learn new green knowledge, focusing on knowledge exchange in green service innovation endeavors. Investigating green innovation in SMEs in Pakistan, Mubeen et al. (2023) emphasize co-value creation based on resources and technology, noting the positive impact of knowledge transfer on green innovation. These findings collectively underscore the complex interplay between knowledge, technology, and resources, the

Table 1 Innovation capabilities in existing literature

Authors (Year)	Methodology	Geographic context	Link (knowledge, technology, resources)	Learn (from and with)	Transfer
Olsson et al. (2010)	Action learning	Medical technology industry in Sweden	Collaboration with partners	Ability to learn in a network	Learning and re-use of knowledge
Lin et al. (2013)	Survey	Taiwanese business unit drawn from diverse industries	Combination practices for innovation capability	Learning capability is enablers for innovation ambidexterity	Innovation practices facilitating learning & knowledge production
Sousa and da Silveira (2017)	Survey	Manufacturers from different sectors in 22 countries	Ability to jointly design services products	Ability to learn from customers	
Behnam et al. (2018)	Case study	Eight innovation projects aimed at social and environmental sustainability in multinational manufacturers in Italy and Spain		Learning from and with external actors in sustainability projects	Transfer information between organizational groups
Pieroni et al. (2021)	Action research	Manufacturing companies in Nordic countries	Linking sustainability business models with business processes		
Hartman et al. (2017)	Interviews with decision makers	Water system transition in Oklahoma, USA	Reconfiguring, described as linking existing knowledge, technology and resources, knowledge sharing capabilities	Learning capabilities for water efficiency and innovation	
Lin and Chen (2017)	Survey	Electronics industry in Taiwan	Capacity to combine and apply new knowledge	Capacity to assimilate & learn new green knowledge	Green knowledge sharing impacts green service innovation
Mubeen et al. (2023)	Survey	Green innovation in SMEs in Pakistan	Creating co-value based on resources and technology		Knowledge sharing positively impacts green innovation

importance of co-learning, and transfer processes across diverse industries and geographic contexts.

Given the prominence of learning in relation to capability development, we explore the application of learning mechanisms in the next section.

2.2 Learning mechanisms

Within the context of capability development, Eisenhardt and Martin (2000), underscore the important role played by learning mechanisms. Their perspective identifies practice, codification, mistakes and pacing as "well known learning mechanisms". Similarly, Coughlan and Coghlan (2011) emphasize the significance of learning mechanisms as crucial organizational capabilities. As argued by Shani and Docherty (2009), the absence of effective learning mechanisms is a key factor in unsuccessful organizational transformations and change interventions. The authors define three broad categories of learning mechanism: cognitive, structural, and procedural.

Cognitive learning mechanisms offer the language, believes, images, principles, and values for contemplating and comprehending learning related issues, consistent with new capabilities. *Structural mechanisms* are physical and technical infrastructures developed to facilitate learning. *Procedural mechanisms* involve institutionalized procedures designed to foster and sustain learning. In the pursuit of cultivating capabilities, organizations and networks may embrace cognitive, structural, and procedural learning mechanisms throughout their developmental endeavors.

2.3 Action learning

The final section of relevant literature relates to action learning. The theoretical action learning foundations are grounded in philosophies of experiential learning, whereby collaborative engagement with others is employed to undertake action-oriented enquiries (Coughlan & Coghlan, 2011). A key part of action learning is the contrast between *puzzles,* and *problem*s (Revans, 1998). *Puzzles* denote difficulties with identifiable and solvable solutions, often amenable to specialized expert guidance. Conversely, *problems* encompass complexities for which no singular solution is feasible.

Action learning proves particularly effective for addressing p*roblems*, as it allows diverse individuals to propose different options for action, aligned with their individual values and principles, and previous experience. Revans (1998) encapsulates the essence of action learning in the formula L (Learning) = P (programmed knowledge) + Q (questioning), emphasizing individual agency in the learning process. Building upon Revans' framework, Vince (2004) contemplates the interplay between action learning and organizational learning, proposing an expansion of the formula to $L = P + Q + O$ (O denoting organizing insight). Vince introduces the concept of organizing insight, incorporating an inquiry into the organizational dynamics shaping the internal context of action learning. Subsequently, Coughlan and Coghlan (2011) extend this formulation to network action learning (NAL), introducing a novel element denoted as IO (insight in an inter-organizational context). The refined formulation reads as $NAL = P + Q + O + IO$, signifying that learning is achieved by partaking organizations and the entire network.

In *this* paper we investigate how the application of NAL by transdisciplinary partners impacts green innovation the development of innovation capability. The research framework in the next section explains how we are planning to approach the research questions.

2.4 Summary and research framework

As a result of this review, we define innovation capabilities as the capacity to link knowledge, technology, and resources for developing new products, and practices. This includes learning from innovation initiatives and transferring and reusing innovation capabilities and knowledge to other initiatives.

However, it appears that at present there is a lack of studies that examine innovation capability in a transdisciplinary context that spans across borders and includes researchers and practitioners working towards addressing the UN Sustainability Goals. Further, we do not know which specific challenges might emerge when working in such a transdisciplinary context while trying to implement novel green technology. While existing literature provides a comprehensive understanding of learning mechanisms, their application in a transdisciplinary environment could further add to this domain.

3 Research design

This section describes our research framework, research methodology and data collection.

3.1 The research framework

The research questions explore how transdisciplinary collaboration by network partners is facilitated by network action learning to impact the development and implementation

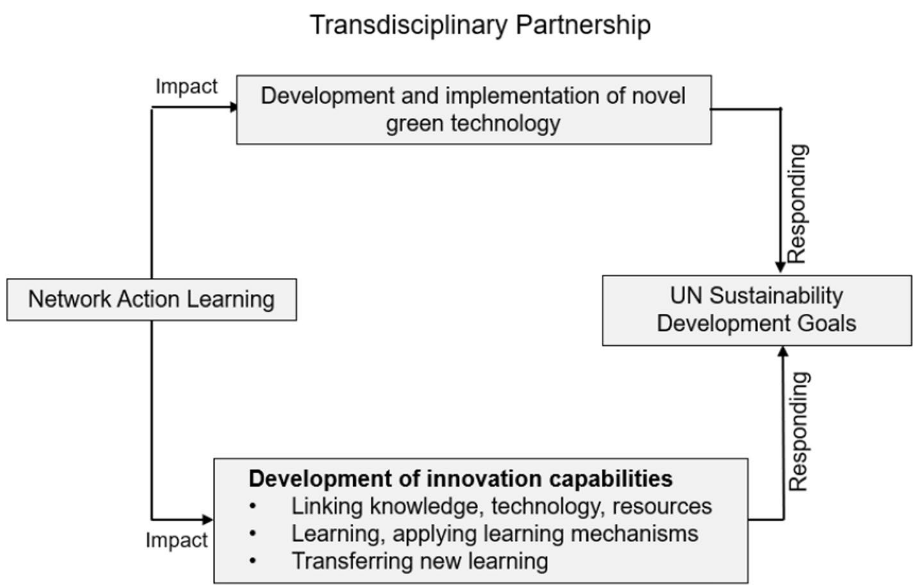

Fig. 1 The research framework

of green innovation, and concurrently, how this approach contributes to the development of capabilities for green innovation. Based on existing innovation capability literature the framework (Fig. 1), guiding our exploration includes the innovation capabilities of linking (knowledge, technology, and resources), learning (applying learning mechanisms), and transferring the learning to other projects. The active nature of the research questions merits a research approach that includes interventions in real-time and the monitoring and reflection on the outcomes.

3.2 Action learning research

Action Learning Research (ALR) is different from traditional action learning. Within the context of action learning, action learners have to fulfill two key requirements: they have to take action and they are committed to learning from this action (Marquardt, 2004). Notably, the fulfillment of these commitments does not inherently lead to the dissemination of acquired knowledge beyond the immediate group. In contrast, ALR introduces an additional commitment—a dedication to augmenting existing actionable knowledge. By contemplating the narrative of the action through a theoretical lens, ALR aims to identify evolving theories that contribute to actionable knowledge (Coughlan & Coghlan, 2011). This reflective process prepares network members for questioning and reflection throughout the innovation and development journey, ultimately fostering innovation capabilities. ALR mandates active engagement with genuine problems, a collaborative approach, a reflective nature characterized by deliberate subjectivity, and a simultaneous commitment to rigorous objectivity regarding the problem and its contextual facts, all leading to practical and implementable outcomes (Willis, 2004).

ALR has been applied in diverse contexts. Set in the food production sector, O'Leary et al. (2017) investigate a pan-European project involving small and medium enterprises (SMEs) in the food production sector, connecting nine national centers across eight European countries. Also applying ALR, Yström et al. (2018) explore the automotive industry in Northern Europe. This network brings together large automotive companies, government agencies, technical consultancy firms, and universities with a shared interest in developing automated vehicles. In Norway, Powell and Coughlan (2020) work with a supplier innovation initiative, existing of a collaborative strategic supplier network with six key companies. The study highlights the importance of collaborative initiatives and knowledge sharing in achieving supply chain improvements. These studies demonstrate the versatility of ALR in facilitating collaboration, knowledge transfer, and innovation within different networks, ranging from SMEs in the food production sector to large players in the automotive and subsea industries. Similar to these studies, ALR emerges as the most suitable research methodology in the context of investigating technology development and innovation within a transdisciplinary network, due to its unique combination of commitment to action, learning, and the explicit commitment to contributing to actionable knowledge. ALR's emphasis on engagement with real-life issues, collaboration, and the production of workable outcomes aligns seamlessly with the complexities of transdisciplinary networks.

3.3 Research context: the Dŵr Uisce project

We explore the research questions in the setting of the Dŵr Uisce project, a cross-border program spanning Ireland and Wales.

The overall purpose of the Dŵr-Uisce program and its sub-projects (organized as work packages) was designed to effectively address the water-energy crisis by “improving the long-term sustainability of water supply, treatment and end-use in Ireland and Wales through innovative technology and collaborative initiatives”. The high energy needs and costs of water treatment and distribution in Ireland and Wales present significant environmental and economic challenges in the regions.

The water industry plays a significant role in exacerbating climate change and is heavily dependent on energy resources. On the other hand, there is still untapped potential to generate energy from both natural water networks (e.g., rivers, streams, and lakes) and artificial ones (e.g., drinking water or irrigation networks).

The project’s objectives include building innovation capability, conducting environmental and economic impact assessments, and developing policy recommendations. It also focuses on developing innovative energy-saving technology platforms, such as smart and low-carbon turbine technology and drain water heat recovery (DWHR) systems. Additionally, the project aims to establish a cross-border transdisciplinary network to stimulate collaboration, knowledge sharing, and economic prosperity, with a focus on commercial application and sustainability in the water sector.

The operational strategy involves three main themes: technology platforms, policy support & guidance, and dissemination & collaboration which were sub-divided into eight workpackages (Fig. 2). The project recognizes the cross-cutting theme of climate change, considering its impact on water resources, energy consumption, and the economy throughout its work.

At the end of the research project the network included 255 members and 124 partners within the Ireland-Wales region. Network members came from professional and support services (water/energy/engineering, consultancies), government authorities,

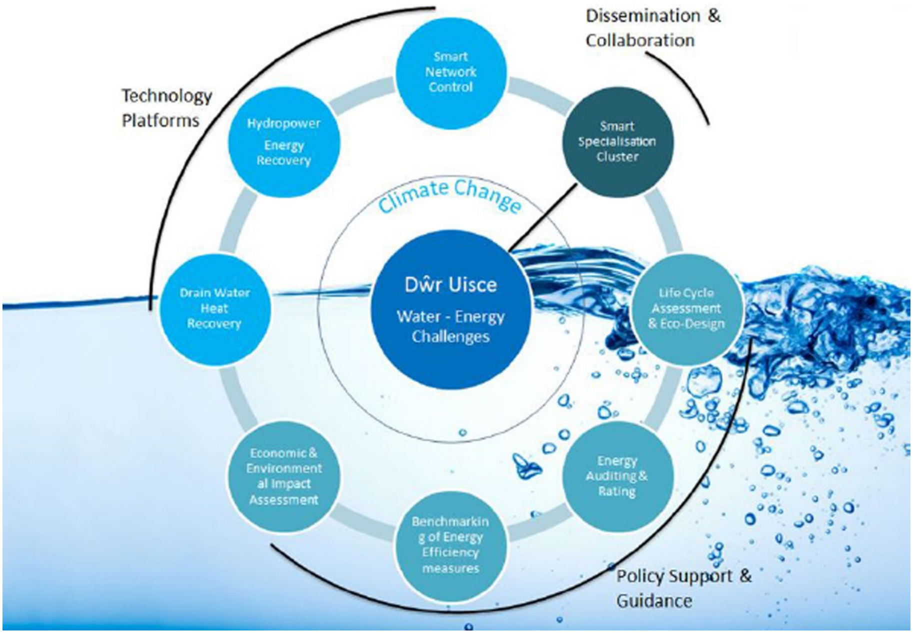

Fig. 2 The Dŵr Uisce project structure

the education sector, utility companies, leisure centers and industries (mainly food & drink).

3.4 Data collection and generation

Between January 2017 and January 2020, we generated and collected data related to context, actions, interactions, and outcomes. Additionally, data were gathered from scientific publications, conference papers, industry publications, and meeting notes. The data generation process involved workshops with researchers and practitioners; the development of scientific publications, conference papers, technical reports, and case studies; as well as interviews with researchers, site managers and industry representatives. Data collection methods also included emails, telephone calls, and online meetings. Throughout the entire process, we assured quality by the disciplined application of action research quality criteria (Willis, 2004; Pasmore et al., 2008; Coughlan & Coghlan, 2011; Klintman et al., 2022).

4 Findings

This section presents our findings organized into distinct categories corresponding to the actions undertaken within work packages: technology platforms, policy support and guidance, and dissemination and collaboration. In the following four sections we illustrate how we learned in action and what specific learning we achieved by addressing *"puzzles"* developing and implementation actions concerning green technology innovations and developing green practice guidelines. Thereafter we illustrate what we learned by addressing the dissemination and collaboration *problem*, within a transdisciplinary cross-border partnership. We emphasize the learning derived from these actions aimed at the development and implementation of novel green technology in Ireland and Wales.

4.1 Green technology innovation (technology platforms theme)

In this section, we detail two sets of actions: developing and implementing pump as turbine (PAT) technology and reducing the energy consumption of existing heat systems. For each, we articulate the *puzzle*, the action taken, and the key learning obtained from our actions.

4.1.1 Developing and implementing pump as turbine technology

The *puzzle*: despite the ever-increasing drive to boost the percentage of energy generation from renewable and cleaner sources over fossil ones, there is still a large untapped potential for new hydro-power installations all over the world. Such potential consists of both natural water networks and artificial ones and is made up of a multiplicity of sites with capacity less than 100 kW. The power output is enough to supply electricity to a single household or to a small village. One of the main obstacles to the construction of such micro-scale hydropower schemes is the relatively high investment cost. Hence, a class of cheaper and more convenient hydro turbines is needed. A technology with the potential to fill in this gap is the Pump-As-Turbine (PAT), which comprises a standard water pump operating in reverse as a turbine. However, the behaviour and applicability of such a device is largely unknown. In the absence of an understanding of PAT behaviour, it was not possible to select an appropriate PAT for a particular operating context.

Action taken: we developed software for selection of an appropriate PAT. The accuracy of the software was tested on a lab scale PAT installation in Ireland, to gain confidence in its suggested selections. Subsequently, the software has facilitated PAT selection as part of the design and installation of two pilot schemes in Ireland and Wales.

Key learnings in action: our experience enabled effective prediction of PAT behaviour, informing power generation installation design. Additionally, insights were gained into obtaining internal support navigating water company management, acquiring necessary licenses for grid connection, and fostering a conducive environment for green technology innovation.

4.1.2 Drain water heat recovery: reducing the energy consumption of existing heat systems

The *puzzle*: water heating is often overlooked in energy saving measures even though it is the second highest reason for energy consumption in typical households (Spriet & McNabola, 2019). Further, the hospitality and food service sectors are major users of warm water in the preparation of meals. The installed water heating systems represent significant investment. Replacing them to save energy and emissions would take time and would require disruptive intervention in busy kitchens. A technology is required that combines straightforward installation, environmental sustainability, and affordability for the operator of a commercial kitchen. Like financial payback, environmental sustainability refers to how the environmental impact from installing the new technology is balanced by the emissions avoided during operation over its lifetime.

Action taken: we began exploring using drain water from commercial kitchens to preheat incoming freshwater. Through empirical measurements in a pilot restaurant in Wales, we collected data identifying the heat recovery potential, cost effectiveness and the environmental impact. Working together and across national boundaries, one researcher based in Ireland provided the design of the heat recovery system, and a prediction of the energy savings. Based on this design and prediction, a second researcher based in Wales calculated the performance for different environmental indicators and the environmental payback time. Together they developed useful practical recommendations for designing a heat recovery system.

Key learnings in action: the combination of a technical, environmental, and economic assessment provided a foundation for a sustainable and user-friendly heat recovery system. Challenges identified include the additional pipework requirements and timing mismatches in heat availability and demand, underscoring the need for innovative solutions in green technology.

4.2 Developing green practice guidelines (policy support and guidance theme)

This section also describes two sets of actions: assessing the climate change effects on drinking water treatment plants and evaluating water-energy performance of wet leisure centers. Again, in each case, we describe the *puzzle*, the action taken, and the learnings in action.

4.2.1 Investigating the effect of climate change on the operational efficiency of drinking water treatment plants

The *puzzle*: climate change affects water supply and quality, potentially impacting the operational efficiency of drinking water treatment plants (DWTPs). Altered water-supply to DWTPs will require different treatment approaches, the degree to which is currently unknown. Having a clearer vision of these implications could inform decision making for DWTP management and planning strategies.

Action taken: we constructed a hydrological model to assess how climate change influences river flows and water quality. A worst-case scenario was defined in terms of future emissions and the corresponding impact on the future climate. Then we took the results from hydrological modelling, and assessed how much energy and finances are currently used to deliver clean and safe drinking water, highlighting the urgency for resilient strategies in green technology solutions.

Learning in action: achieving holistic sustainability (environmental, social, and economic) in areas such as water supply requires transdisciplinary collaboration, bridging environmental factors and water industry operations, fostering collaboration in the pursuit of effective green technology solutions.

4.2.2 Investigating water-energy performance and efficiency of wet leisure centers

The *puzzle:* wet leisure centers are centers with swimming pools. There is a considerable scope to reduce the water and energy consumption and associated emissions.

Action taken: a water-energy audit exercise of six centers in the UK Identified efficiency improvement potential. Site-specific reports and a rating system were developed for intervention strategies showing practical steps in green technology integration.

Learning in action: the audit identified specific water and energy consumption patterns. Additionally, it identified opportunities for green technology improvement and efficiency gains to help reduce both water and water-related energy consumptions, carbon emissions, operational costs, and ecological footprint.

4.3 Dissemination and collaboration

This section focuses on the dissemination and collaboration work package which differs from but is connected to the technology platforms and policy guidance and support themes. To implement green innovation, involvement from various stakeholders such as environmental scientists, engineers, geographers, economists, water and energy supply site managers, technology suppliers, and government authorities is needed at different stages of project development. Communication, collaboration, learning and integration of views from multiple partners and other stakeholders can be a challenging *problem* for a transdisciplinary network.

This *problem* has been reported on in previous papers deriving from Dŵr Uisce related research, offering solutions towards effectively addressing transdisciplinary collaboration challenges.

4.3.1 Dissemination of learning in action

To date, we have captured these insights in five papers, presented at different conferences, since the beginning of the project. The act of drafting these papers has been a valuable learning mechanism, consistent with O'Leary et al., (2017). Firstly, the writing process allowed for questioning and reflection by the researchers. Secondly, the papers have become boundary objects, allowing for integrating knowledge areas in the action learning process. The focus of the papers consists of the following topics:

1. Creating a climate for transdisciplinary collaboration through action learning
   Our first paper explored building collaboration within a network through action learning (Siva et al., 2017). We asked the question how to generate, capture and implement learning in a transdisciplinary partnership. We focused on creating a conducive climate for collaboration drawing on Frischer (1993), noting dimensions like challenge, trust, and shared vision.
2. Maintaining a mindset of respectful and inclusive learning in action
   Later in 2017, we delved into a transdisciplinary network for developing eco-design in the water sector (Coughlan et al., 2017). Action learning emerged as a crucial mechanism, stressing the importance of diverse participants, and ensuring everybody has a voice while respecting each other's expertise.
3. Develop knowledge integration strategies
   Our subsequent paper by Siva et al. (2018) explored how learning through demonstration contributes to ongoing innovation. We highlighted the necessity of knowledge integration strategies, organization structures, access to knowledge, artefacts, and co-location.
4. Exploring knowledge integration in transdisciplinary networks
   Also in 2018, we studied how demonstration in a transdisciplinary network supports continuous innovation (de Almeida Kumlien et al., 2018). A practical knowledge integration strategy involves demonstration, collaborative prototyping and learning mechanisms.
5. Learning how to innovate with the "right" people, structures, and climate
   Confirming and expanding on previous findings, we discovered the importance of the "right" people, structures, and climate in a transdisciplinary partnership (de Almeida Kumlien et al., 2019).

Building on these publications, this research focuses the role of network action learning in green technology development and implementation, outlining our findings in the following section.

4.3.2 *The problem*: collaboration in a transdisciplinary cross-border partnership

The aim of the Dŵr Uisce cross-border network was to provide a forum for collaboration, demonstration, debate, knowledge transfer, and green innovation throughout the duration of the project and beyond.

Throughout the duration of the project, several events and outreach activities (e.g., workshops, demonstrations, conference, and online webinars) were delivered. Overall, network action learning has been applied as the underlying approach to the knowledge sharing and learning purposes of the network. As outlined earlier, any engagement with industry members can involve action learning (Coughlan & Coghlan, 2011; Revans, 1998; Vince, 2004). Partners in the Dŵr Uisce cross-border network were provided the space, time and environment to learn from each other thus allowing them to engage in network action learning, addressing problems where no single solution exists.

For example, in the development of green Pump-as-Turbine (PAT) technology, the research team established two demonstration sites: one located on a group water scheme site in Ireland and the other situated on the grounds of a conservation charity site in Wales.

During transdisciplinary workshops and demonstration site visits in Ireland many issues emerged, including the need for a significant amount of data, challenges in accessing technology suppliers, ensuring the availability of key stakeholders on meeting dates, application of communication tools accessible to all partners, moderating conflicting priorities, and logistical challenges in remote areas.

At the Welsh demonstration site, challenges emerged due to adverse weather conditions affecting access to the site, the effects on wildlife, the necessity for developing a common language, meaningful to both practitioners and researchers, competing priorities between tourist access and researcher access, and access restrictions to financial data from technology suppliers.

Researchers from diverse disciplines travelled to multiple sites, demonstrating and explaining novel technology and practices, addressing issues with partners through a series of in-person and online meetings. Discussions and implementation actions followed in which network members addressed obstacles. To transfer learning from green technology sites (e.g., the PAT in Ireland) to other locations, videos taken by drones, were shared, adhering to local privacy laws and other legal obligations. 3D virtual tours (e.g., on the Welsh conservation charity site) enabled network members not able to engage in person to join collaborate meetings. Prototypes were used to share learning and enable problem solving across borders.

5 Reflection and discussion

We organize our reflection into two sections: emerging factors impacting the development and implementation of green innovation and developing innovation capabilities.

5.1 Impact factors shaping development and implementation of green technology

We explored the factors impacting the application of novel energy recovery technology. We illustrate the factors on an Ishikawa Diagram, a tool to analyze factors impacting on a specific outcome in a complex setting. The overall categories are people, environment, material/information, machines/technology, measurements, and methods. Figure 3 summarizes the impact factors we came to understand when carrying out the research, developing and implementing novel technologies.

Our reflection suggests that there were multiple impact factors in each category affecting the application of a novel technology. Some were typical for any type of innovation (People, behavioral, financial constraints, communication), others arose due to the complexities of transdisciplinary cross-border network innovation: language, environmental factors, diversity of stakeholders, variety of technological options, and ways of organizing. These factors emerged as obstacles or enablers.

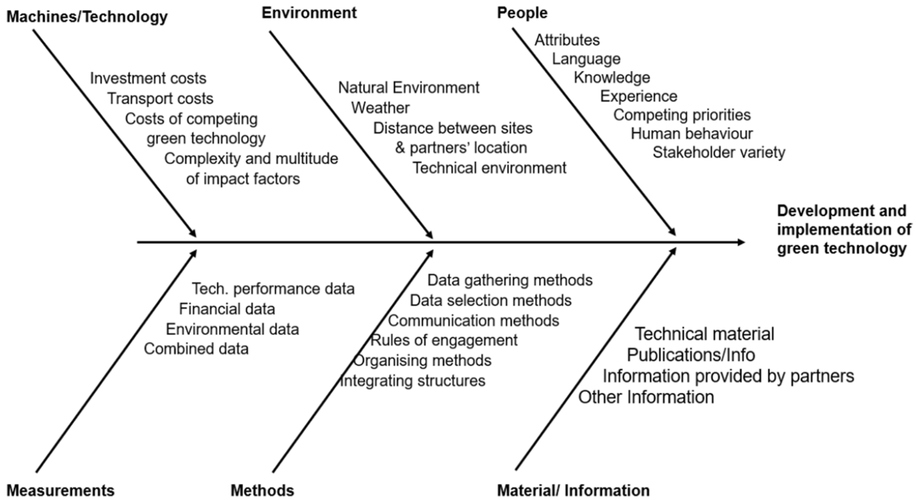

Fig. 3 Factors impacting the development and implementation of green technology

For example, the variety of stakeholders presented both challenges and support. To advance projects, input was needed from many stakeholders which delayed progress. Yet, the access to a variety of information also enabled improvement of project outcomes. The multitude of contacts and relationship with suppliers, site owners, government agencies and media were, in many cases, an advantage to progress novel technology. However, great care had to be given to ensure that all necessary stakeholders were informed and involved in relevant events, outcomes of trial runs or decisions to be made. Industry and expertise related language made it necessary to frequently calibrate and explain terminology.

The quality of collaborative relationships played a crucial role. Given the diversity of partners (academics, business managers, technology suppliers, local government authorities), different frames (Agramont et al., 2019) were applied to assess the value of a green technology, for example novelty, investment payback time, acceptability for future operational application without a research agenda, and adhering to local environment requirements. Facilitating effective relationships that considered all frames involved the application of organizing methods mindful of diversity, including various communication modes, rules of engagements, organizing structures, logistics planning, and sharing of lessons learned from demonstration sites.

Table 2 highlights the contributions from network partners in addressing arising problems. The table shows the previously applied impact factor categories and the knowledge, technology, and resources partners contributed. The information provided indicates that while the cross-border, transdisciplinary network required tackling many obstacles, the contributions of network members were diverse and useful in addressing green technology implementation.

5.2 Developing capabilities for green innovation

The second part of the research question addresses developing capabilities for green innovation. As previously indicated, innovation capabilities comprise three dimensions, linking knowledge, technology and resources, learning, applying learning mechanisms, and

Table 2 Impact factors shaping development and application of green technology and network partners' contributions

Partners	Impact factors					
	People	Environment	Machines	Measurements	Methods	Material
Engineers (Ireland)	Resources Individuals with specific relevant engineering knowledge and empirical research skills	Knowledge Grid connections Site suitability	Knowledge Investment costs Technology & transportation costs Technology PAT technology DWHR technology Resources Laboratories Prototypes	Knowledge Technical performance data Economic analysis of energy demand Life cycle assessment Technology Measuring software	Knowledge Data gathering methods Data selection methods	Knowledge Suitability of technical material Commercially available technology
Geographers (Ireland, Wales and beyond)	Resources Individuals with specific relevant geographical knowledge and empirical research skills	Knowledge Accessibility of natural resources Accessibility of water intake site Unexpected waterflow Weather patterns Distance between sites and actor locations, Travel suitability	None identified	Knowledge Geographical data climate projections data Water abstraction licence/data National river flow historic data European soil database Corine EU land cover data	Knowledge Soil and water assessment methods Resources Soils and water assessment tools	Resources Existing data of life cycle assessment

Table 2 (continued)

Partners	Impact factors					
	People	Environment	Machines	Measurements	Methods	Material
Environmentalists (Ireland & Wales)	Resources Individuals with specific relevant environmental knowledge and empirical research skills	Knowledge Impact on wildlife Quality of surface water	None identified	Knowledge Environmental data Financial analysis of cost to deliver high quality drinking water in the future Economic analysis of demand management interventions Combined technical, environmental & economic assessment	Knowledge Physical data collection and auditing methods of wet leisure centres Resources Newly developed eco-design toolkit Soils and water assessment tool (SWAT)	Resources Data concerning the complexity and multitude of impact factors on the research environment in Ireland and Wales, and comparable global data
Management & action researchers (Ireland)	Resources Individuals with specific relevant management and action research knowledge and empirical research skills	None identified	None identified	Knowledge Public engagement data Economic assessment	Knowledge Action learning principles Organising methods Resources Time for project coordination, negotiating, facilitating debate Time for extensive communications via different channels and platforms Planning tools events Technology Shared cloud access	Previous project related publications Lessons learned from demonstration sites Publications, media material repository

Table 2 (continued)

Partners	Impact factors					
	People	Environment	Machines	Measurements	Methods	Material
Site managers (Ireland and Wales)	Resources Individuals with knowledge and experience of site-specific operational details and general related industry details	Knowledge Local conditions Resources Local resources Access to research and demonstration sites	Resources Local resources and equipment Research and demonstration sites	Knowledge Availability of data from demonstrations sites Water abstraction licence/data River flow historic data Financial data	Knowledge Day-to-day management of operational sites Strategic site management Knowledge and experience to address customer and community needs	Knowledge Customer and community usage and attendance Resources Site specifications Reports on past performance, future trends
Suppliers (Ireland, Wales, and beyond)	Resources Individuals with knowledge and experience of available green technology and software	Knowledge Local conditions	Knowledge Investment costs, costs of competing green technology Technology Green technology and software Resources Green equipment and devices	Knowledge Green technology measurements Financial data	Knowledge Technology implementation methods Performance data monitoring methods	Knowledge Customer preferences in specific geographical areas Resources Sales databases

Table 2 (continued)

Partners	Impact factors					
	People	Environment	Machines	Measurements	Methods	Material
Local Authorities (Ireland and Wales)	Resources Individuals with knowledge and experience on policy frameworks, and operational site governance requirements	Knowledge Local conditions	None identified	None identified	None identified	Resources Dŵr Cymru offering data and advice, giving the work a sense of realism Denbighshire County Council (time, access to centres, access to site and duty managers, etc Irish water providing data and site requirements
Universities (Ireland and Wales)	Resources Individuals with knowledge and experience of facilitating conferences and workshops	None identified	Resources Research funding Research facilities Meeting space	None identified	None identified	Resources Access to databases Access to academic publications
Funding agency						Resources Research funding

PAT Pump-as-turbine, *DWHR* Drain-water heat recovery transferring knowledge. In each category we identified subcategories that are relevant in a transdisciplinary network. We explore each in turn.

5.2.1 Linking knowledge, technology, and resources

Innovation capabilities identified in the literature include an ability to link knowledge, technology and resources (e.g. Lin & Chen, 2017). Appendix 1 illustrates how we linked knowledge, technology, and resources provided by network members, but also included sources external to the network. Our linking practices involved combining environmental modelling with financial assessment tools through freely available online information, such as technical data libraries. Resources procured from research funds were instrumental in advancing new technology, complemented by contributions from water-energy site managers. Specific examples, such as PAT (Ireland and Wales) and DWHR (Ireland & Wales), illustrate the amalgamation of diverse knowledge types, technology, and resources in the pursuit of green innovation.

5.2.2 Learning aided by the application of learning mechanisms

Creating innovation capabilities was enabled by applying learning mechanisms: cognitive, structural and procedural (Shani & Docherty, 2009), as shown in Appendix 2. In the context of our cross-border transdisciplinary partnership, these mechanisms were crucial in addressing challenges, potential, and limitations of technology platforms. Specifically *cognitive learning mechanisms* were employed to establish effective communication among network partners. This involved generating a shared vision, creating a common interpretation of data output, and developing a unified language for transdisciplinary and cross-national communication. We learned that in contrast to organizational cognitive learning mechanisms, different scientific knowledge bases needed to be integrated. *Structural learning mechanisms* supported our collaborative efforts. Virtual and physical meeting spaces, such as online sites, discussion groups, workshops, and conferences, were established to facilitate collective learning of new practices. For example, in the case of PAT technology in Ireland and Wales, structural learning involved coordinating with suppliers, builders, project partners, and site owners through various mediums like online platforms and physical meetings. Our *procedural learning mechanisms* provided learning routines for collective learning. They included publications of learning results, periodic newsletters, routine group meetings for activity updates, daily, weekly, and monthly reports on data output and progress. For instance, DWHR in Ireland and Wales involved routine procedural learning through the development of an eco-design toolkit based on data from both projects.

5.2.3 Transferring knowledge

Another innovation capability is the ability to transfer what was learned to consecutive and later projects or other stakeholders that may find the research work relevant and useful (Lin & Chen, 2017; Mubeen et al., 2023). Knowledge was transferred from individual researchers to several stakeholders, from collaborative research teams within the project to the wider network, and the network to the external scholarly community and the general public (Appendix 3). The variety of media types facilitated transfer of what was learned, to a wider audience, within the Dŵr Uisce partnership and beyond. Overall, the evident ability to link resources and disseminate emerging knowledge is consistent with dynamic capabilities (Eisenhardt & Martin, 2000; Teece, 2019), in particular green dynamic capabilities (Mubeen et al., 2023).

Additionally, we came to appreciate boundary spanning actors (Baaken et al., 2020; Chakkol et al., 2018). These were individuals able to facilitate communication, collaboration, and knowledge exchange during our meetings, workshops, and conferences, fostering the integration of insights and expertise. Furthermore, we applied boundary objects (Schleyer et al., 2017; Snyder et al., 2010) for example prototypes and videos to enable partners to apply and share their assessment. Our applied boundary spanning practices (Snyder et al., 2010) such as demonstration events and conferences encouraged knowledge exchange, as well as highlighting obstacles that were previously not taken into account. Overall, the success of developing and implementing green innovation in a transdisciplinary network depended not only on the substantial knowledge available, but also on how integration mechanisms were managed, addressing the collaboration *problem*.

6 Contribution

In this research we addressed the questions, how can a transdisciplinary partnership through network action learning impact the development and implementation of green technology and practices? Additionally, how does this approach contribute to the concurrent development of capabilities for green innovation?

Based upon our empirical findings and reflection, we outline how we have responded to the UN Sustainable Development Goals and offer several contributions to theory and to practice. We relate our contributions to existing studies.

6.1 Contribution to theory

As described and reflected upon in the previous sections, ALR has presented the foundation for critical inquiry, generating insights for solving a real-life *problem*. We identified factors which impact the development and implementation of green technology and practices as summarized in Fig. 4.

6.1.1 NAL facilitating the development and implementation of green innovation

Initially we applied a research framework (Fig. 1) to guide our research concerning the relationships of interest when engaging in exploring and applying novel technology. In the process of our research, the NAL Framework for facilitating the development and implementation of green innovation evolved (Fig. 4), now containing factors influencing the

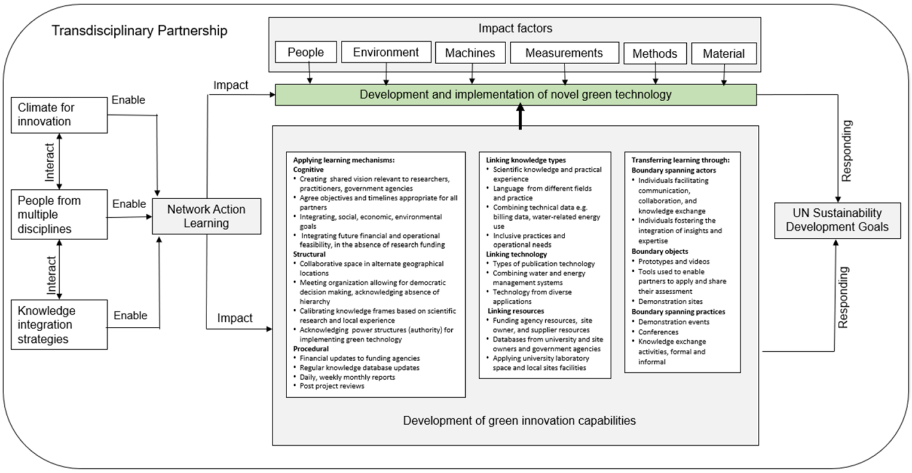

Fig. 4 Network action learning framework for developing and implementing green innovation

development process. We discovered that by applying NAL, diverse partners were able to contribute solutions to development and implementation problems by learning in a network, in action. Table 2 indicates that partners from diverse backgrounds and different frames (Agramont et al., 2019) contributed in several ways to address factors impacting on the development of green innovation. Our findings contribute to Moallemi et al's. (2020) research agenda who investigated the benefits of genuine stakeholder engagement and transdisciplinary co-learning between scientists and stakeholders.

6.1.2 Capability development for green innovation

Authors such as Börjesson and Elmquist (2011), Ali AlShehail et al. (2022), and Mubeen et al. (2023) emphasize the significance of green innovation capability development and call for further research on how these capabilities are developed in complex settings. Our research responds to this call, offering insights how in practice green innovation capabilities are developed in a transdisciplinary, cross-border network. Additionally, we contribute to innovation capability theory (Börjesson et al., 2014; Teece, 2019), adding that network action learning is one effective way to develop innovation capabilities, in transdisciplinary partnership.

This multiple-year study identifies the factors impacting on green innovation development and implementation, and how network partners address obstacles by *linking* knowledge types (practical and theoretical), resources, and technology. We address therefore the need to identify pre-conditions that enable knowledge sharing (Lin & Chen, 2017). Additionally, we respond to Mubeen et al.'s (2023) call to research green innovation capability development longitudinally.

The research provides details on the capability of *co-learning* (Moallemi et al., 2020) in a network, applying cognitive, structural, and procedural learning mechanisms, specific to green innovation in transdisciplinary partnership. Our research work shows that these learning mechanisms are not only applicable in a single organisation (Cirella et al., 2016;

Shani & Docherty, 2009; Dreyer-Gibney et al. 2023), in an interorganizational network (Coughlan & Coghlan, 2011), but also in a cross-border transdisciplinary partnership. We found with our research that as a cognitive learning mechanism, partners need to integrate social, economic, and environmental considerations in addressing the complexities of green innovation. As structural learning mechanisms, the creation of collaborative spaces in varying geographical locations becomes essential, facilitating access and inclusivity. Moreover, the integration of scientific knowledge and operational and local experience is necessary and requires well-defined, continuous co-learning. The organizational structure of such collaborations should be characterized by democratic decision-making processes, recognizing the absence of hierarchical norms. Another element is the acknowledgment of power dynamics, recognizing that green technology implementation ultimately depends on local, operational, and customer acceptability.

Our research shows that *transferring* what was learned to other projects, through boundary spanners, applying boundary objects and practices also enhances green innovation capability (Baaken et al., 2020; Chakkol et al., 2018; Schleyer et al., 2017; Snyder et al., 2010). Our empirically derived NAL Framework illustrates this process.

6.2 Methodological contribution

This study enhances comprehension regarding the importance of Action Learning Research (ALR) in fostering critical examination and uncovering solutions for practical challenges. Our exploration delved into the influence of action learning on green innovation within a network, illustrating its role in cultivating green innovation capabilities. The method employed for collecting, generating, and applying data underscores the efficacy of structured participation and collaboration within the network. The resulting practical insights adhere to the benchmarks of exemplary research, characterized by rigor, reflection, and relevance, as articulated by Coughlan and Coghlan (2011).

6.3 Managerial implications, and contribution to public knowledge

In this research we addressed several Sustainability Goals, Goal 6 (Clean water and sanitation), Goal 9 (Industry, innovation, and infrastructure) and Goal 17 (Partnerships for the goals). The substantive output of the research has practical and positive implications for water and energy supply, and those who are stakeholders in the distribution process. However, the study has shown also how sustainable, effective, and collaborative ways to respond to the Goals have been developed. Our research and the resulting NAL framework offer effective and practical ways to researchers, practitioners, and policy makers. It shows the obstacles that may arise when embarking on developing and implementing green technology. It also shows the contributions network partners make during the implementation. Additionally, the research demonstrates that by addressing sustainability goals, network partners develop innovation capabilities to tackle such *problems*.

There are several "practitioner" audiences for this study: the network partners, such as a charitable organization, government agencies, water-energy site owners, technology suppliers. Furthermore, communication on social and general media (TV, newspapers) illustrated the relevance of our research to the general public. This communication has also increased visibility of what NAL can achieve to address the water-energy crisis.

Managers charged with developing and applying novel technology can use the evolved NAL framework for the application of novel technology and assess what obstacles may emerge when doing so. Further, both practitioners and researchers may apply the framework when attempting to respond to the UN Sustainability Goals.

6.4 Practical outcomes

As Appendix 4 indicates there are several tangible outcomes associated with the research program. They include the creation of low-cost micro-hydropower technology and design software for water pipe networks, with successful field implementation. Wastewater heat recovery technology was also innovated, significantly reducing energy costs for hot water activities in business and industry. The implementation of smart control algorithms for water pipe networks ensures sustainable water and energy resource management through optimization techniques. Additionally, the study assessed life cycle impacts of water-related activities, identifying ways to minimize environmental impacts, and benchmarks the water sector in Ireland and Wales against regional and international standards. The research further contributed by developing energy audits and ratings for water-related industries and domestic users, raising awareness of the impact of water use choices on energy consumption and sustainability. The evaluation of climate change on the water sector in Ireland and Wales highlights projected effects on water resources, quality, and energy needs. The dissemination of project findings and water-energy nexus issues, contributed to enhanced water and energy efficiency awareness in water services both regionally and internationally.

7 Conclusion and implications

Humanity encounters fundamental challenges stemming from climate change and water scarcity, *problems* that defy resolutions in isolation. Our research advocates for a comprehensive methodology, capable of addressing these *problems* holistically, aligning with the UN Sustainability Goals.

This study demonstrated the manner in which a cross-border, transdisciplinary partnership, comprising researchers and practitioners from both industry and local governments effectively tackled the identified challenged, thereby fostering green innovation and practices.

This study has limitations. Only the impact of network partners was included in the study. Other influencing factors such as the national culture and legislative framework was excluded and only alluded to by the network partners' knowledge and experience. Further research could investigate how the level of technological development and sustainability orientation of the countries would impact green innovation.

Appendix 1

See Table 3.

Table 3 Linking knowledge, technology, and resources

Project	Linking knowledge types	Linking technology	Linking resources
Green technology innovation: pump as turbine (Ireland & Wales)	Linking performance data from various sources Combining researcher knowledge and practitioner experience Linking knowledge type: performance data, practitioner experiences, local government data Supplier knowledge Financial data	Linking PAT selection algorithm with software from MATLAB	Managing and resourcing construction of project technology by site managers based on researcher specifications University made available laboratory space and devices Linking researchers' prototypes with existing water distribution site technology
Green technology innovation: drain water heat recovery (Ireland & Wales)	Linking knowledge of how to conduct a life cycle assessment with knowledge of heat recovery systems Combing language and terminology from different fields	Bringing together shower heat recovery system technology with a commercial kitchen environment technology	Linking resources from the project with those from a conservation charity to install a heat recovery system
Investigating climate change effects on drinking water treatment plants' operational efficiency (Ireland, UK, incl. Wales)	Combining separate existing knowledge bases relating to hydrological impacts on DWTPs and the operations of such plants, in terms of their economic and energy performance	Linked DEA model input with output from the SWAT model	Taking climate scenarios from the UK Climate Projections 2018 data and extracted for use in the specific catchments studied
Water-energy performance and efficiency of wet leisure centers (UK, incl. Wales)	Using metering and billing data with audit, population, and visitor/customer data to estimate water-related energy use	Combining water management with energy management systems	Sharing documentation between council, duty managers and researchers

Table 3 (continued)

Project	Linking knowledge types	Linking technology	Linking resources
Dissemination (Ireland, Wales & beyond)	Applying content marketing theories, identifying main categories of content that can attract online audience & tailoring program information accordingly	Linking different types of publication technology	Applying social media tools with information provided from researchers and practitioners
Collaboration Ireland, Wales & beyond	Applying a combination of inclusive practices to ensure that collaborative knowledge exchange meetings, events, are inclusive, respectful and polite Combining and synthesizing variety of ideas	Applying a combination of digital communication tools to facilitate collaboration between partners and stakeholders	Linking individual partners and stakeholders to facilitate collaboration within the Dŵr Uisce partnership and beyond Applying financial resources to enable face-to-face cross-border collaboration

Appendix 2

See Table 4.

Table 4 Learning, applying learning mechanisms

Project	Cognitive Learning mechanisms	Structural learning mechanisms	Procedural learning mechanisms
Green technology innovation: pump as turbine (Ireland & Wales)	Understanding of modelling of new technology behaviour based on statistical analysis	Coordinating with the suppliers, builders, project partners and site owners Using pilots (demonstration sites)	Internal reporting between the Dŵr Uisce team and other project stakeholders. Publication on website, conferences and workshops
Green technology innovation: drain water heat recovery (Ireland & Wales)	Understanding the potential and limitations	Visiting sites to view installations to see components for inclusion in LCA. Taking measurements on sight. Manufacturer information retrieved online	Developing an eco-design toolkit, based data from both projects Publication on website, conferences and workshops
Investigating climate change effects on drinking water treatment plants' operational efficiency (Ireland, UK, incl. Wales)	Deepening of understanding on DWTP operations and technologies required in order to develop economic and energy efficient suggestions for future management	Sharing cloud access to data/resources. Meetings between with other researchers to exchange expertise on how approaches could complement each other	Internal reporting between the Dŵr Uisce team and other project stakeholders Publication on website, conferences, and workshops
Water-energy performance and Efficiency of Wet Leisure Centres (UK, incl. Wales)	Understanding the water and energy use and provisioning of wet leisure centres	Meetings with site managements to discuss sites and what to address in reports. Meetings with council to discuss zero net carbon declaration and targets	Internal reporting between the Dŵr Uisce team and other project stakeholders Publication on website, conferences, and workshops
Dissemination (Ireland, Wales & beyond)	Analytic tools on Twitter/X and project website, understanding of our audience's characteristics and user behaviours	Categorise users' behaviours that help to develop an effective way of tailoring content and communicating with them	Developing a series of thematic tweets in advance and scheduled for publishing
Collaboration Ireland, Wales & beyond	Facilitating the creation of a shared vision by running workshops and brainstorming events	Facilitating role in creating a common language Capturing new developments in meeting logs and online databases	Facilitating learning exchange by organising events, workshops, meetings

Appendix 3

See Table 5

Table 5 Transferring learning

Project	Activity	What learning was transferred to later/consecutive project?	How was learning transferred?
Green technology innovation: pump as turbine (Ireland & Wales)	Development of PAT selection software to transferred to lab experimentation with PATs	Confidence in PAT design, knowledge on how to size the lab equipment	Partners discussing and sharing data
Green technology innovation: drain water heat recovery (Ireland & Wales)	Heat recovery transferred to Environmental impact	Projected energy recovery and required equipment	Partners discussing and sharing data
Investigating climate change effects on drinking water treatment plants' operational efficiency (Ireland, UK, incl. Wales)	Energy auditing transferred to climate change impact	Water quality outputs from hydrological modelling directly act as inputs to the DEA model	Partners discussing and sharing data
Water-Energy performance and efficiency of wet leisure centers (UK, incl. Wales)	Auditing water use transferred to identifying under-performing centers	Water use data and water use behaviour information were used to estimate water-related energy use and recommendations for under-non-performing sites	Data gathering and analysis, reporting, workshop for site managers conferences and academic publications
Dissemination (Ireland, Wales & beyond)	Transfer of knowledge from all work package Publications (academic journals, trade magazines, general newspapers) Social Media (Twitter, Instagram, LinkedIn) Other Media (Dŵr Uisce website, TV documentaries, videos) Virtual meeting spaces (shared online sites, online discussion groups and websites, skype meetings and conference calls) Physical meeting spaces (face-to-face informal and formal meetings, demonstration sites, workshops, project launches group meetings, conferences)		
Collaboration Ireland, Wales & beyond	Facilitating learning capture and transfer by organizing events, workshops, meetings, other communication tools	Facilitating role, ensuring all learning is comprehensively captured for use in other/later projects and beyond	Facilitating role in finding the most suitable way to transfer captured learning Drone footage, videos, posters, virtual 3D tours, hackathons

Appendix 4

See Table 6.

Table 6 Summary of green innovation—results by country *Source* Dŵr Uisce synapsis report 2023

	Work packages	Summary	Results in Ireland	Results in Wales	Results in other countries
1	Micro-Hydropower tech & design software	Developed low-cost micro-hydropower technology and design software for water pipe networks, from concept to field implementation	Implemented Feasibility testing in mines	Implemented	Applicable
2	Wastewater heat recovery technology	Innovated wastewater heat recovery technology, reducing energy costs for hot water activities in business and industry, with successful field implementation	Implemented	Implemented	Applicable
3	Smart Control Algorithms for Water Networks	Created smart control algorithms for water pipe networks, ensuring sustainable management of water and energy resources through optimization techniques	Applicable	Applicable	Applicable
4	Life cycle impact assessment	Assessed life cycle impacts of water supply and use activities across sectors, identifying ways to reduce environmental impacts in the water sector	Assessment conducted	Assessment conducted	Applicable Conducted in the UK
5	Water sector benchmarking	Benchmarked the water sector in Ireland and Wales against regional and international standards, offering insights to enhance water and energy efficiency in water services	Benchmarking conducted	Benchmarking conducted	Applicable
6	Energy audits for water users	Developed energy audits and ratings for water-related industries and domestic users, raising awareness of the impact of water use choices on energy consumption and sustainability	Audits conducted	Audits conducted	Applicable
7	Climate change impact assessment	Evaluated climate change impacts on the water sector in Ireland and Wales, highlighting projected effects on water resources, quality, and energy needs	Impact assessment conducted	Impact assessment conducted	Applicable
8	Project dissemination & outreach	Disseminated project work and related water-energy nexus issues widely in the Ireland-Wales region and internationally through online resources, stakeholder engagement, and outreach activities	Dissemination & outreach activities conducted	Dissemination & outreach activities conducted	Dissemination & outreach activities conducted

Acknowledgements Dŵr Uisce is part funded by the European Regional Development Fund through the Ireland-Wales Cooperation programme 2014-2020.

The installation of the demonstration sites has been possible thanks to the data provided and generated by and in collaboration with the Blackstairs Group Water Scheme, EPS, The National Federation of Group Water Schemes in Ireland, National Trust Wales, ABP Food Group Ltd.

Funding Open Access funding provided by the IReL Consortium.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

References

Agramont, A., Craps, M., Balderrama, M., & Huysmans, M. (2019). Transdisciplinary learning communities to involve vulnerable social groups in solving complex water-related problems in Bolivia. *Water, 11*(2), 385.

Aguiñaga, E., Henriques, I., Scheel, C., & Scheel, A. (2018). Building resilience: A self-sustainable community approach to the triple bottom line. *Journal of Cleaner Production, 173*, 186–196. https://doi.org/10.1016/j.jclepro.2017.01.094

Ali AlShehail, O., Khan, M., & Ajmal, M. (2022). Total quality management and sustainability in the public service sector: The mediating effect of service innovation. *Benchmarking: an International Journal, 29*(2), 382–410.

Ali, S. M., Appolloni, A., Cavallaro, F., D'Adamo, I., Di Vaio, A., Ferella, F., Gastaldi, M., Ikram, M., Kumar, N. M., & Martin, M. A. (2023). Development goals towards sustainability. *Sustainability, 15*(12), 9443.

Baaken, T., Garomssa, H., Helmer, J., Petzol, N., & Troutt, M. P. (2020). *What are spanning boundaries agents and why are they so important to the future of the knowledge society?* The FH Münster – University of Applied Sciences, Science-to-Business Marketing Research Centre.

Barth, M., Jiménez-Aceituno, A., Lam, D. P., Bürgener, L., & Lang, D. J. (2023). Transdisciplinary learning as a key leverage for sustainability transformations. *Current Opinion in Environmental Sustainability, 64*, 101361.

Behnam, S., Cagliano, R., & Grijalvo, M. (2018). How should firms reconcile their open innovation capabilities for incorporating external actors in innovations aimed at sustainable development? *Journal of Cleaner Production, 170*, 950–965. https://doi.org/10.1016/j.jclepro.2017.09.168

Börjesson, S., & Elmquist, M. (2011). Developing innovation capabilities: A longitudinal study of a project at Volvo cars. *Creativity and Innovation Management, 20*(3), 171–184. https://doi.org/10.1111/j.1467-8691.2011.00605.x

Börjesson, S., Elmquist, M., & Hooge, S. (2014). The challenges of innovation capability building: Learning from longitudinal studies of innovation efforts at Renault and Volvo Cars. *Journal of Engineering and Technology Management, 31*, 120–140. https://doi.org/10.1016/j.jengtecman.2013.11.005

Chakkol, M., Karatzas, A., Johnson, M., & Godsell, J. (2018). Building bridges: Boundary spanners in servitized supply chains. *International Journal of Operations & Production Management, 38*(2), 579–604. https://doi.org/10.1108/IJOPM-01-2016-0052

Cirella, S., Canterino, F., Guerci, M., & Shani, A. B. (2016). Organizational learning mechanisms and creative climate: Insights from an Italian fashion design company. *Creativity and Innovation Management, 25*(2), 211–222. https://doi.org/10.1111/caim.12161

Coughlan, P., & Coghlan, D. (2011). *Collaborative strategic improvement through network action learning*. Edward Elgar Publishing.

Coughlan, P., Gallagher, J., Siva, V., Coghlan, D., & McNabola, A. (2017). *Developing integrated low-carbon and smart energy innovations in water and energy: Creating a smart specialisation cluster*. IPDMC 2017, Reykjavik.

D'Amore, G., Di Vaio, A., Balsalobre-Lorente, D., & Boccia, F. (2022). Artificial intelligence in the water–energy–food model: A holistic approach towards sustainable development goals. *Sustainability, 14*(2), 867.

de Almeida Kumlien, A., Coughlan, P., Mc Nabola, A., Novara, D., & Fernandes, I. (2018). *Demonstrating learning in action in a water and energy smart specialisation cluster*. CINet 2018, Dublin.

de Almeida Kumlien, A., Coughlan, P., Dreyer-Gibney, K., & McNabola, A. (2019). *Learning to innovate through action learning, collaborative prototyping and demonstration*. IPDMC, Leiceister, UK.

Dreyer-Gibney, K., Coughlan, P., & Coghlan, D. (2023). Staff engagement through action learning enabling the practice of developing new services in a publicly funded university. *Creativity and Innovation Management, 32*(4), 584–602. https://doi.org/10.1111/caim.12574

Eisenhardt, K. M., & Martin, J. A. (2000). Dynamic capabilities: What are they? *Strategic Management Journal, 21*(10–11), 1105–1121. https://doi.org/10.1002/1097-0266(200010/11)21:10/11%3c1105::AID-SMJ133%3e3.0.CO;2-E

Frischer, J. (1993). Empowering management in new product development units. *Journal of Product Innovation Management, 10*(5), 393–401.

Handbook of Collaborative Management Research Toward a More Rigorous Reflective and Relevant Science of Collaborative Management Research SAGE Publications Inc. 1 Oliver's Yard 55 City Road London EC1Y 1SP 567–582.

Hartman, P., Gliedt, T., Widener, J., & Loraamm, R. W. (2017). Dynamic capabilities for water system transitions in Oklahoma. *Environmental Innovation and Societal Transitions, 25*, 64–81. https://doi.org/10.1016/j.eist.2016.12.004

Klintman, M., Jonsson, A., Grafström, M., & Torgilsson, P. (2022). Academia and society in collaborative knowledge production towards urban sustainability: Several schemes—three common crossroads. *Environment, Development and Sustainability*, 1–20.

Koop, S. H., & van Leeuwen, C. J. (2017). The challenges of water, waste and climate change in cities. *Environment, Development and Sustainability, 19*(2), 385–418.

Lin, H.-E., McDonough, E. F., III., Lin, S.-J., & Lin, C.Y.-Y. (2013). Managing the exploitation/exploration paradox: The role of a learning capability and innovation ambidexterity. *Journal of Product Innovation Management, 30*(2), 262–278. https://doi.org/10.1111/j.1540-5885.2012.00998.x

Lin, Y.-H., & Chen, Y.-S. (2017). Determinants of green competitive advantage: The roles of green knowledge sharing, green dynamic capabilities, and green service innovation. *Quality & Quantity, 51*(4), 1663–1685. https://doi.org/10.1007/s11135-016-0358-6

Marquardt, M. J. (2004). *Optimizing the power of action learning*. Davies-Black Publishing.

Moallemi, E. A., Malekpour, S., Hadjikakou, M., Raven, R., Szetey, K., Ningrum, D., Dhiaulhaq, A., & Bryan, B. A. (2020). Achieving the sustainable development goals requires transdisciplinary innovation at the local scale. *One Earth, 3*(3), 300–313.

Mubeen, A., Nisar, Q. A., Patwary, A. K., Rehman, S., & Ahmad, W. (2023). Greening your business: Nexus of green dynamic capabilities, green innovation and sustainable performance. *Environment, Development and Sustainability.* https://doi.org/10.1007/s10668-023-03574-6

O'Leary, D., Coughlan, P., Rigg, C., & Coghlan, D. (2017). Turning to case studies as a mechanism for learning in action learning. *Action Learning: Research and Practice, 14*(1), 3–17.

Olsson, A., Wadell, C., Odenrick, P., & Bergendahl, M. N. (2010). An action learning method for increased innovation capability in organisations. *Action Learning: Research and Practice, 7*(2), 167–179. https://doi.org/10.1080/14767333.2010.488328

Pasmore, W. A., Stymne, B., Shani, A. B., Mohrman, S. A., & Adler, N. (2008). The promise of collaborative management research. *Handbook of collaborative management research*, 7–31.

Pieroni, M. P. P., McAloone, T. C., & Pigosso, D. C. A. (2021). Developing a process model for circular economy business model innovation within manufacturing companies. *Journal of Cleaner Production, 299*, 126785. https://doi.org/10.1016/j.jclepro.2021.126785

Powell, D. J., & Coughlan, P. (2020). Rethinking lean supplier development as a learning system. *International Journal of Operations & Production Management, 40*(7/8), 921–943.
Revans, R. W. (1998). *ABC of action learning*. Lemos and Crane.
Schleyer, C., Lux, A., Mehring, M., & Görg, C. (2017). Ecosystem services as a boundary concept: Arguments from social ecology. *Sustainability, 9*(7), 1107.
Schouten, B., Klerks, G., Hollander, M. D., & Hansen, N. B. (2021). *Action design research shaping university-industry collaborations for wicked problems* In: Proceedings of the 32nd Australian Conference on Human-Computer Interaction, Sydney, NSW, Australia. doi: https://doi.org/10.1145/3441000.3441078
Shani, A. B., & Docherty, P. (2009). Learning by design. In P. Docherty, M. Kira, & A. B. Shani (Eds.), *Creating sustainable work systems.*
Siva, V., Coughlan, P., & McNabola, A. (2017). *Building collaboration within a smart specialisation cluster through action learning*. SOSC 2017, Bangalore.
Siva, V., Coughlan, P., & McNabola, A. (2018). *Knowledge integration strategies within a smart specialization cluster: Enabling sustainability in the water-energy nexus*. EurOMA 2018, Budapest.
Snyder, W. M., & Wenger, E. (2010). Our world as a learning system: A communities-of-practice approach. *Social Learning Systems and Communities of Practice*, 107–124.
Sousa, R., & da Silveira, G. J. (2017). Capability antecedents and performance outcomes of servitization: Differences between basic and advanced services. *International Journal of Operations & Production Management, 37*(4), 444–467.
Spriet, J., & Mc Nabola, A. (2019). Decentralized drain water heat recovery from commercial kitchens in the hospitality sector. *Energy and Buildings, 194*, 247–259.
Teece, D. J. (2019). A capability theory of the firm: An economics and (strategic) management perspective. *New Zealand Economic Papers, 53*(1), 1–43. https://doi.org/10.1080/00779954.2017.1371208
Vince, R. (2004). Action learning and organizational learning: Power, politics and emotion in organizations. *Action Learning: Research and Practice, 1*(1), 63–78. https://doi.org/10.1080/1476733042000187628
Wehn, U., & Montalvo, C. (2017). Exploring the dynamics of water innovation: Foundations for water innovation studies. *Journal of Cleaner Production, 171*, 1–19.
Willis, V. J. (2004). Inspecting cases against Revans' 'gold standard' of action learning. *Action Learning: Research and Practice, 1*(1), 11–27.
Yström, A., Ollila, S., Agogué, M., & Coghlan, D. (2018). The role of a learning approach in building an interorganizational network aiming for collaborative innovation. *The Journal of Applied Behavioral Science, 55*(1), 27–49. https://doi.org/10.1177/0021886318793383
Zarei Mohammad, H., Carrasco-Gallego, R., & Ronchi, S. (2019). To greener pastures: An action research study on the environmental sustainability of humanitarian supply chains. *International Journal of Operations & Production Management, 39*(11), 1193–1225. https://doi.org/10.1108/IJOPM-12-2018-0703

Authors and Affiliations

Katrin Dreyer-Gibney[1] · Paul Coughlan[1] · David Coghlan[1] · Szu-Hsin Wu[2] · Aisha Bello-Dambatta[3] · Richard Dallison[3] · Aonghus McNabola[4] · Daniele Novara[4] · Annum Rafique[5] · Isabel Schestak[3] · Jan Spriet[6] · Nathan Walker[3] · Prysor Williams[3]

✉ Katrin Dreyer-Gibney
dreyergk@tcd.ie

Paul Coughlan
COUGHLNP@tcd.ie

David Coghlan
DCOGHLAN@TCD.IE

Szu-Hsin Wu
swu001@dundee.ac.uk

Aisha Bello-Dambatta
a.bellodambatta@bangor.ac.uk

Richard Dallison
r.dallison@bangor.ac.uk

Aonghus McNabola
AMCNABOL@tcd.ie

Daniele Novara
NOVARAD@tcd.ie

Annum Rafique
a.rafique@bham.ac.uk

Isabel Schestak
isabel.schestak@bangor.ac.uk

Jan Spriet
SPRIETJ@tcd.ie

Nathan Walker
afpafd@bangor.ac.uk

Prysor Williams
prysor.williams@bangor.ac.uk

[1] Trinity Business School, Trinity College, The University of Dublin, Dublin, Ireland

[2] University of Dundee, 1-3 Perth Road, Dundee, UK

[3] School of Natural Sciences, Bangor University, Wales, UK

[4] Department of Civil Structural and Environmental Engineering, Trinity College Dublin, The University of Dublin, Dublin, Ireland

[5] City Region Economic and Development Institute (City-REDI), University of Birmingham, Birmingham, UK

[6] Brussels Environment, Environmental Services, Brussels, Belgium