



Creating knowledge about food-water-energy nexus at a local scale: A participatory approach in Tulcea, Romania

Dragos Balaican^{a,*}, Iulian Nichersu^a, Iuliana.I. Nichersu^a, Andrea Pierce^b, Olga Wilhelmi^c, Pia Laborgne^d, Edward Bratfanof^a

^a Danube Delta National Research and Development Institute, Romania

^b University of Delaware, USA

^c National Center for Atmospheric Research, Boulder, CO, USA

^d ElFER Europäisches Institut für Energieforschung EDF-KIT, Germany

ARTICLE INFO

Keywords:

Food-water-energy nexus
Urban
Sustainability
Stakeholder engagement

ABSTRACT

The concept of the food-water-energy nexus (FWE nexus) presents an alternative paradigm to traditional sectoral approaches for managing natural resources while promoting climate resilience and sustainable development. Applying the FWE nexus in the urban context, however, has been limited due to the complexity of the concept and the challenges of integrating interdisciplinary and local knowledge with the governance structure available to resource managers. This case study from Tulcea, Romania explores the participatory process used to analyze the dynamic character of the FWE nexus in the context of current societal challenges and practices. Participatory research activities presented in this study focused on the 'food' component of the FWE nexus (i.e., local vegetable markets), while exploring connections with water (irrigation and water quality) and energy (consumption and renewable energy sources). The results illustrate the utility of adopting a transdisciplinary integrative approach to understanding the nexus, particularly for local-scale applications of the FWE system integrations within broader sustainable development initiatives.

1. Introduction

Food, water, and energy are critical resources necessary for human survival but facing severe pressures from population growth, urbanization, economic development, and climate change. The concept of the food-water-energy (FWE) nexus emerged out of international conversations on resource security and sustainable development (Hoff, 2011). The FWE nexus offers an analytic framework to better understand and systematically analyze the interactions between resource systems, the natural environment, and human activities across sectors and scales (FAO et al., 2014). McCallum et al. argued that a nexus approach is required when attempting to understand the complex interrelationships between food, water, and energy systems (McCallum et al., 2020).

Nexus scholars increasingly recognize that it is not only the interactions between resource sectors that comprise the FWE nexus but also the social actors, whose behavior interacts with the environment and economy to produce the FWE nexus (Bleischwitz et al., 2018; Tye et al., 2022). As complex socio-ecological systems of their own, cities provide a particularly challenging environment to study, producing a

sub-field of research specifically on the urban FWE nexus for reviews, see (Artioli et al., 2017; Tye et al., 2022; Newell et al., 2019).

Practically, scholars argue that adopting an FWE nexus management approach can support a transition to sustainability (Frantzeskaki et al., 2019), by reducing trade-offs and generating additional benefits that outweigh the transaction costs associated with stronger policy integration across sectors (Hoff, 2011). In cities, the urban FWE nexus approach could assist in improving both vertically and horizontally integrated urban governance, building upon existing development strategies, managing trade-offs through integrated urban planning, and fostering behavioral change (Artioli et al., 2017; Lehmann, 2018; Jones and White, 2022). Nexus management efforts align well with multiple sustainable development goals (SDGs), such as ending hunger (SDG2), clean water and sanitation (SDG7), affordable and clean energy (SDG8), and sustainable cities and communities (SDG11) (Bleischwitz et al., 2018).

FWE nexus research has expanded considerably over the past two decades since the concept's introduction (Tye et al., 2022). Previous studies have demonstrated that a variety of analytical tools can be used to describe and analyze the FWE nexus components and connections at

* Corresponding author.

E-mail address: dragos.balaican@ddni.ro (D. Balaican).

<https://doi.org/10.1016/j.envsci.2022.12.013>

Received 4 November 2021; Received in revised form 22 November 2022; Accepted 16 December 2022

Available online 7 January 2023

1462-9011/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

various scales. Examples include life cycle assessment (Al-Ansari et al., 2015; Salmoral and Yan, 2018; Notarnicola et al., 2017; Seidel, 2016) qualitative system analysis approach based on Causal Loop Diagrams (CLD) (Stollnberger et al., 2020) computational general equilibrium analysis (Fan et al., 2018; Wittwer, 2010), economic modeling (Jalilov et al., 2016; Al-Riffai et al., 2017; Shi et al., 2019), and input-output analysis (Feng et al., 2017; Wu and Chen, 2017; Fang and Chen, 2017). Using this knowledge, the FWE nexus literature has largely focused on technical or managerial solutions for FWE systems integration.

A frequently acknowledged limitation of existing research is how to practically implement an FWE nexus approach (Wahl et al., 2021), given data availability, processing, and capacity constraints at the local level. A related weakness of existing nexus research has been how to engage stakeholders in what is largely a technical exercise, both to build support for collaborative FWE governance and to collect relevant local knowledge that could improve the effectiveness of future management strategies (Wahl et al., 2021; Jones and White, 2022). Local (tacit) knowledge is a vital resource for both understanding and addressing pressing social-ecological challenges of our time, including food-water-energy security (Apetrei et al., 2021).

The broader field of sustainability science has increasingly embraced multiple forms of knowledge, and specifically “action-oriented” knowledge, in its quest to facilitate sustainability. One recent proposed approach for the field “rejects technocratic solutions to complex sustainability challenges and foregrounds individual and social learning” (Caniglia et al., 2020), p.93. In this vein, nexus scholars have begun developing novel frameworks and participatory research approaches to generating action-oriented knowledge and promoting social learning (Laborgne et al., 2021a; Wahl et al., 2021; Yan and Roggema, 2019; Johnson and Karberg, 2017; Menny et al., 2018). A recent review (Tye et al., 2022) found only 4 urban nexus studies that used participatory methods and only 2 studies that recommended stakeholder participation in the future development of nexus solutions (Wahl et al., 2021).

Additional urban nexus studies employed stakeholder interviews with experts and practitioners, but only one study directly engaged local residents (non-experts) in the research (Wahl et al., 2021).

Prior studies found that focusing on the issues arising within one sector (e.g., food) and establishing connections to the other two (e.g., water and energy) facilitates the discussions about FWE nexus (Tye et al., 2022). Food is commonly used as an entry point into the FWE nexus, being a more tangible nexus component compared with water and energy, especially at the urban scale. Food represents an important part of the nexus research, with some scholars arguing that food management is not given the same importance in urban planning and policy making as water and energy (Hoff, 2011). By comparing food sustainability scores of different food systems, Jacobi et al. (2020) underlined the importance of going beyond the classical focus on production and instead addressing food sustainability issues as part of a comprehensive food system approach, from production to consumption and beyond (i.e., waste management).

The purpose of this study is to describe the implementation of an urban FWE nexus approach adopted in one city to address local knowledge and governance capacity limitations through a participatory process that engages stakeholders and citizens. This paper responds to a recent call for nexus scholars to focus on the practicalities of implementing an engaged urban nexus approach. Specifically, “Linking context-specific descriptive-analytical research with solution-innovation approaches can optimize overall efforts, exploit synergies, and minimize trade-offs in time, energy, and funding. Coordinating research in this way would enable purposes and objectives that are co-defined with stakeholders on the ground to be aligned with learning and new knowledge that can be efficiently integrated into models and tools” (Wahl et al., 2021), p.671. Here, the participatory process enabled the co-definition of the research aims, informed design of an interactive nexus data collection tool, and provided substantive input for the tool that enabled an illustrative analysis of the local vegetable market, its FWE nexus intersections, and possibilities for

strategic investments that could facilitate a sustainable urban transition through the food system.

The following sections detail the participatory process and methods employed in the research (Section 2), its results (Section 3), and reflections on lessons learned in the discussion and conclusions (Section 4).

2. Methods

This paper describes the results of a participatory research process used to investigate the urban FWE nexus and its dynamics in one case city: Tulcea, Romania. The following sections review the Tulcea case context, the data collection process used within the case, and the functionalities of the data collection tool developed during the research.

2.1. The case context

Tulcea is a coastal city in Romania with a current population of nearly 87,000 inhabitants (Tulcea County Directorate of Statistics, 2022).

Tulcea was one of three case cities selected for a larger collaborative international project seeking to make the urban FWE nexus more understandable through innovative approaches for local knowledge co-creation and stakeholder engagement (Laborgne et al., 2019; EIFER I European Institute for Energy Research, 2020). The larger project had the following objectives: 1) explore the interrelationships between the FWE sectors in the case cities, including the actors and institutions involved in the food, water, and energy sectors; 2) develop a participatory process for eliciting stakeholder knowledge about the FWE nexus in the case cities and 3) integrate stakeholder knowledge into an online tool for collecting data and building awareness about the nexus and its management in the case cities.

Tulcea presents a unique case for exploring the FWE nexus due to its extensive local connections to water, food, and energy resources. In Tulcea, the Danube River ends its journey through Europe, creating one of the largest wetlands on Earth known as the Danube Delta, before it flows into the Black Sea (Fig. 1). The city has been an important harbor since ancient times.

2.2. The data collection process

To achieve the project’s research objectives, we adopted a participatory research process involving stakeholders in the design and execution of the research (Yan and Roggema, 2019; Vaughn and Jacques, 2020; Menny et al., 2018). The research employed both qualitative and quantitative data collection techniques, as described below and summarized in Table 1. The data collection process was monitored and continuously evaluated by the project leads based on observations and user evaluation forms.

2.3. Initial participatory phase

The project began with an initial round of stakeholder interviews and document analysis intending to build the knowledge base on the FWE nexus systems, its elements, and its dynamics in each case city. In Tulcea, six semi-structured key informant interviews were conducted in June–July 2019 with key informants already known to the research team, representing local and national-level stakeholders. The interviews with government officials and representatives of water, food and energy sectors in Tulcea were conducted face-to-face, by phone, or by email, at the discretion of the key informant. The interviews helped to identify key actors in the FWE sectors and their roles in the city’s food, water, or energy systems. Practically, the interviews also helped to ensure that the project had local relevance to decision-makers in Tulcea.

Each case city in the larger project identified one FWE system as an entry point in investigating the local nexus (EIFER I European Institute for Energy Research, 2020). For Tulcea, the initial nexus entry point was water, based on the project team’s prior technical knowledge.

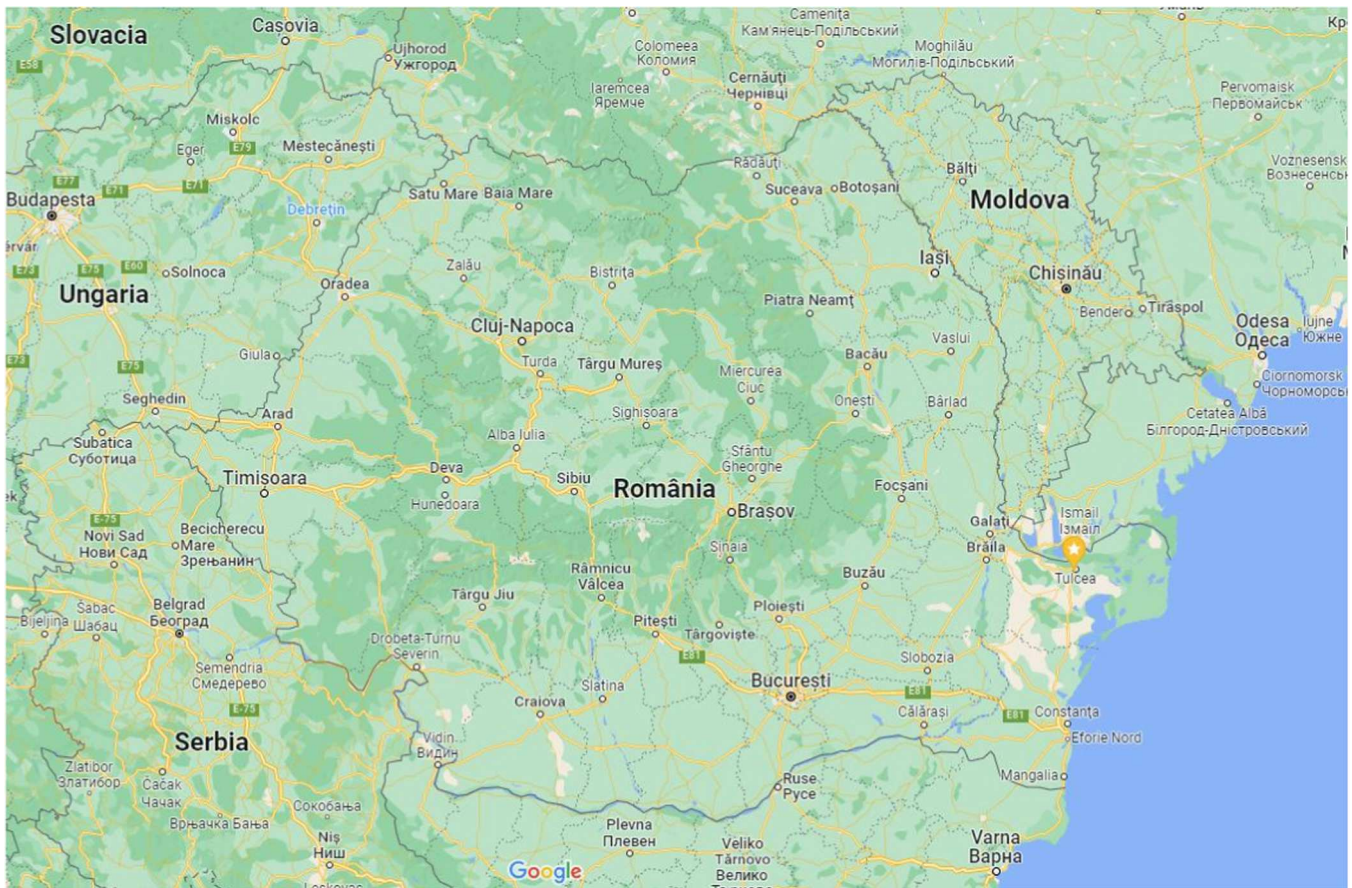


Fig. 1. Physical Map of Romania with Tulcea City position highlighted (Google.Geobasis-DE/BKG (2009) available at <https://www.google.com/maps/@46.2998983,23.8533142,6.98z>).

Specifically, the team identified the area around Zaghen Lake as a key nexus feature in Tulcea that combined irrigation for small agricultural holdings with ecological restoration. After consultation with stakeholders during the initial key informant interview phase, the FWE nexus entry point shifted to food. The broader aim of the research in Tulcea became to increase the visibility of interlinkages between local producers and consumers and facilitate community behavioral change toward a more sustainable local food system.

The research team next convened a public workshop (in person) in July 2019. The main goal of this first workshop was to establish a participatory process and to raise awareness about the FWE nexus. The researchers worked, with citizens and representatives of public and private sector organizations working together to co-design the next phases of research, refine the FWE nexus entry point as the food system, explore interrelations between nexus sectors at the administrative level, and consider needs for a data collection and analysis tool. Participatory methods such as participatory modeling, brainstorming and visioning were used throughout the workshop and helped to facilitate discussions and organize the information related to the key workshop questions. The workshop participants also explored how the FWE nexus could support Tulcea's transition to a sustainable city (Cronje et al., 2011; Jacobi et al., 2020). A total of 43 persons attended the first workshop, with 10 organizers and moderators (members of the research team) and 33 participants. The participants included stakeholders who participated in the initial key informant interviews or were recommended to the research team during the interviews. Information about the event was also disseminated in local newspapers and on social media to ensure that all interested persons could participate.

2.4. Tulcea tool development and testing phase

During the project, an online data collection and analysis tool “Creating Interfaces - Tulcea” (hereafter the Tulcea tool) was co-designed using information, needs, and feedback gathered from stakeholders combined with requirements from the project team and its partners (see Fig. 2). The mobile-friendly online tool was developed by 52°North, a project partner, using an open-source framework, designed to combine elements of online mapping, citizen science, and volunteered geographic information (Sheppard et al., 2020).

The Tulcea tool development process followed a user-centered design approach for continuous improvement. A prototype was presented to participants at the first workshop in July 2019, described above. The participants provided input about the content, design, and usability of the prototype. Their feedback was incorporated into the next version of the Tulcea Tool and then tested with project partners during a virtual workshop in May 2020. With the feedback from project partners, a third version was tested with a small group of Tulcea citizens in July 2020. Participant feedback was encouraged and suggested changes were integrated, where possible.

2.5. Tool use and analysis phase

A fully revised version of the tool was deployed for use in an illustrative analysis of the local food system with the focus on vegetable markets (presented below in Section 3.1). The analytic objective was to trace the origin of some vegetables offered locally to reveal the resource links between the three nexus sectors (food, water, energy), the distance traveled to consumers, and the energy and environmental impacts of

Table 1
Data collection process summary.

Data Collection Techniques	Purpose	Participants
<i>Initial participatory phase:</i>		
Semi-structured interviews (June–July, 2019)	Build knowledge base of FWE systems, actors, and local governance	6 key informants representing: Mayor's Office, Directorate for Agriculture and Rural Development, National Agency for Land Development, Sanitary Veterinary and Animal Safety Division, Agro Markets (local food produce retailer), and AQUASERV (water provider)
Public workshop (July 2019)	Continue building knowledge base of FWE systems, actors, and local governance Guide tool design and development	10 organizers & moderators 33 participants representing: <i>Local authorities:</i> Mayor's Office, Prefecture; Danube Delta Biosphere Reserve Administration; Association for Inter-Community Development Integrated Territorial Investments Danube Delta (ADI ITI DD) <i>National authorities:</i> National Health Agency, National Agency for Environmental Protection <i>Water sector:</i> AQUASERV, SGA Tulcea (manages irrigation systems in Tulcea County) <i>Energy sector:</i> ENERGOTERM Tulcea (energy supplier) <i>Food sector:</i> Sanitary Veterinary and Animal Safety Division (DSVSA), local farmers <i>News media</i> 10 members of the research team
<i>Tulcea Tool development and testing phase:</i>		
Online workshop (May 2020)	Pre-testing the Tulcea Tool for content and usability	11 project partners from Europe and North America representing public and private organizations and diverse disciplinary backgrounds
Online workshop (July 2020)	Testing the Tulcea Tool with potential users for content usability	15 citizens from Tulcea
<i>Tulcea Tool use and analysis phase:</i>		
Interviews and surveys (September–October 2020)	Obtain information for the illustrative local vegetable market analysis	52 local food producers and retailers
<i>Tulcea tool final development and presentation:</i>		
Public workshop (October 2020)	Present results to stakeholders	17 participants representing: <i>Local authorities:</i> Mayor's Office; Prefecture; Danube Delta Biosphere Reserve Administration; <i>National authorities:</i> National Health Authority; National Agency for Environmental Protection; ADI ITI DD; Local Markets Administration; <i>Water sector:</i> AQUASERV <i>Food sector:</i> Local Markets Administration, local farmers

their production, distribution, and purchase.

This phase involved mapping of the grocery stores and face-to-face or phone interviews with 52 stakeholders in September–October 2020 (Table 1). The stakeholders represented vegetable producers and sellers, national store chains, local store chains and local regulatory authorities. The interviews lasted an average of 15 min. The first part of the

interview introduced the FWE nexus concept and described how respondents can contribute to its development and integration into the Tulcea governance system. In the second part of the interview, participants completed a short survey related to the local vegetable market. The questionnaire asked about the respondent's type of activity performed (e.g., producers, local store chains, national store chains), the availability of five seasonal vegetables, the origin of those vegetables, annual production and sales data, water consumption and energy use. The questionnaires were anonymous, with the respondents being identified only by the type of activity.

2.6. Final tool development and presentation

In October 2020, the final version of the Tulcea tool, populated with data about local food producers and local vegetable markets' locations was presented publicly in an online stakeholder workshop. The highlights from the local vegetable market analysis were discussed along with the comparison of choosing high-mileage products over locally produced ones and their energy use. Fifteen participants attended the workshop, representing local and national-level stakeholders. The participants discussed the utility of the Tulcea tool and provided user feedback through a short survey on its usefulness, attractiveness, and ease of use. The participants' suggestions were included in the final design, where possible.

3. Results

As described above, this project was developed with the objective to raise awareness among local stakeholders and decision-makers of the urban FWE nexus, interlinkages between the food, water, and energy systems, and opportunities for a sustainable transition. The next two sections describe the final data collection tool and its illustrative use in the analysis of the local vegetable market in Tulcea.

3.1. About the final tool

The Tulcea tool, being an interactive, experimental data collection tool was developed using an iterative process and a user-centered design. The ultimate purpose of the tool was not immediately evident but emerged through the stakeholder engagement process. Specifically, the main purpose of the tool became to collect data that could establish connections between food producers and consumers. The tool can recommend certain producers to potential consumers based on a consumer's profile and improves the visibility of local food products to the community, which can inform personal and institutional behavior.

Additional information relevant to the FWE nexus is collected in the tool that could be analyzed in more detail later. The consumer profile form collects annual energy and water use, including wastewater. The producer profile form collects water consumption data and asks if they use irrigation. For instance, one small local vegetable producer consumed 350 cubic meters of water and 300 kilowatt-hours of electricity to grow nearly 12,000 kg of produce per year (Fig. 3). This producer is also located approximately 20 kilometers from the point of final sale for its produce.

All users can add information on what type of energy they use, whether they use renewable energy, and if not if they might consider its use in the future. The purpose of mapping the individual consumption of citizens and small local producers is to create a baseline of information that could be optimized over time as part of a sustainable urban transition (Frantzeskaki et al., 2019).

Finally, users have the opportunity to reflect on the usefulness, attractiveness, and content of the Tulcea tool through an embedded Feedback Form, where the results could inform the tool's future development. Because the project has now ended, further tool development will depend on action from local authorities.

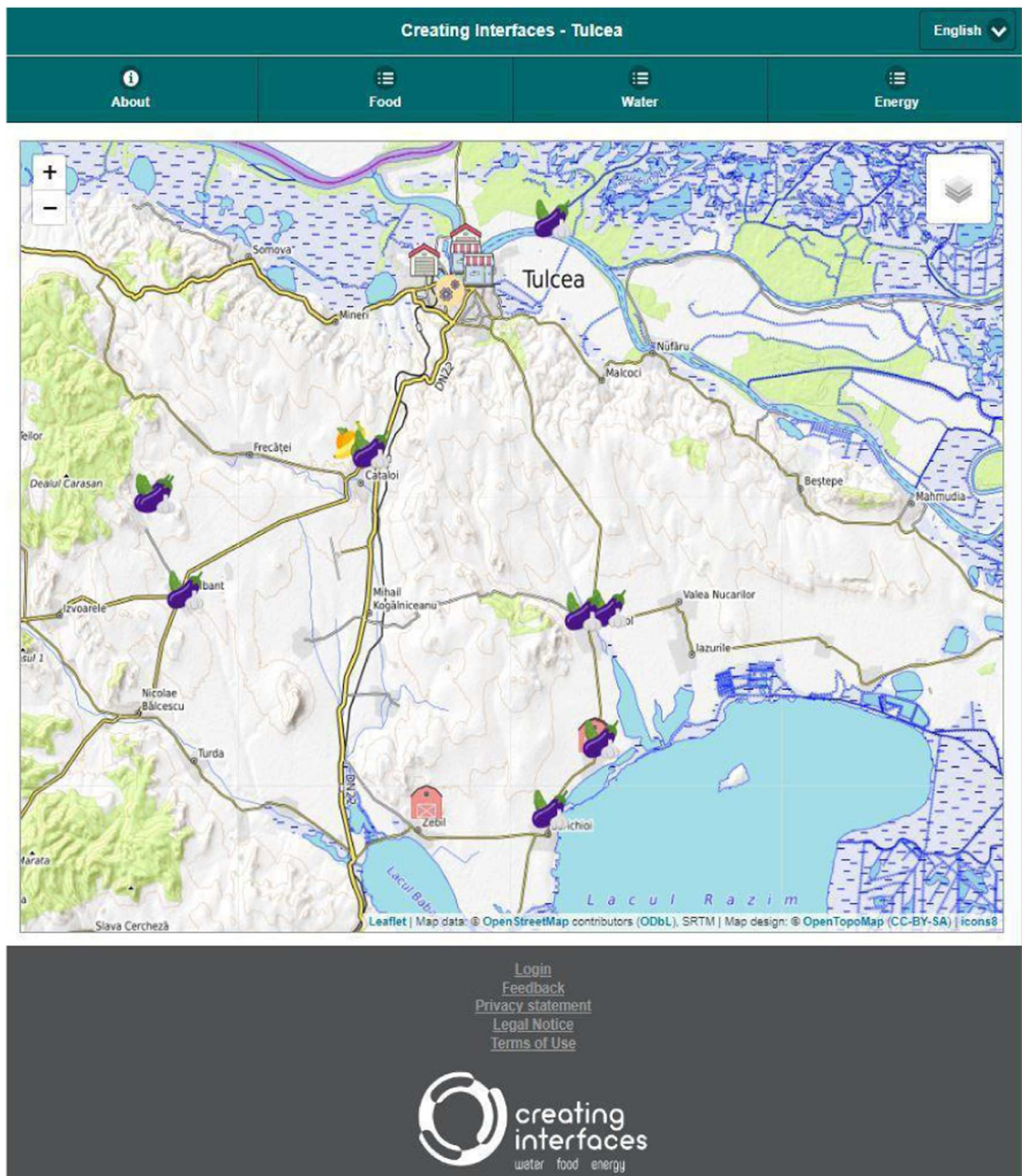


Fig. 2. Screenshot of the Tulcea Tool showing the distribution of vegetable markets and the main components of the user interface.

3.2. Illustrative analysis of the local vegetable market in Tulcea

Food represents an essential piece of the urban FWE nexus in Tulcea. Similar to prior research (Tye et al., 2022) food has proven to be the most tangible component of the FWE nexus for local stakeholders. A complete analysis of Tulcea's food system and its nexus connections is beyond the scope of this paper. Instead, this paper provides an illustrative analysis of the local vegetable market, which is a central feature of Tulcea's food system, using data obtained from 52 interviews and surveys (described above in 2.5). In addition to having a direct

connection to the FWE nexus via food production and consumption, the local vegetable market influences the water sector through irrigation used to grow vegetables and wash vegetables for sale, and the energy sector through the consumption necessary for the production, storage, transport, and marketing of food products.

3.3. Local vegetable sales and origins

According to study participants, approximately 950 tons of tomatoes, 410 tons of cucumbers, 240 tons of kapia peppers, 515 tons of

The screen capture shows a web application interface for 'Macovei Geta'. The top navigation bar includes 'Home', 'About', 'Food', 'Water', and 'Energy'. The main content area is divided into two sections. The left section contains a form with various fields for producer information, and the right section displays a map of the area.

Name	[Redacted]
Type	Deținător de certificat de producător
Category	
Main product(s)	ardei, roșii, castraveți, vinete
Address	Trestenic
Telephone	
E-mail	
Website	
Location Mode	Punct pe hartă / Point on Map
Latitude	45.079553
Longitude	28.592449
GPS Accuracy	53.94
Google Maps	Navigate to location
Do you use water for irrigation?	Yes
Do you have interest to use water for irrigation?	
Water quantity (in m ³ per year)	350
Water quality	From source
Average electrical consumption (in kWh per year)	300
Distance: producer → storage → sale point (km)	20
Production (in kg/ha per year)	3000
Surface (in ha)	4
Uses	Other
Use of fertilizer	Natural
Storage point	
Sale point	PIAȚA SF. GHEORGHE

Pictures of products/location

Fig. 3. Screen capture of information gathered from a local producer.

onions, and 855 tons of potatoes are sold annually in Tulcea (Fig. 4). Tomatoes and onions are more frequently sold directly from producers (farmers), while onions and potatoes are sold more frequently by chain grocery stores. Sales of kapia peppers are relatively similar across the three retailer types of producers, small businesses, and chain stores.

During the year, vegetable sales fluctuate (Fig. 5) with better sales reported by respondents in April-May and August-September especially for local producers selling at agro-markets and for overall city-level sales. Sales are reportedly more stable throughout the year for chain grocery stores. Lower sales during the winter season in agro-markets and

DISTRIBUTION OF VEGETABLE SALES AT TULCEA CITY LEVEL

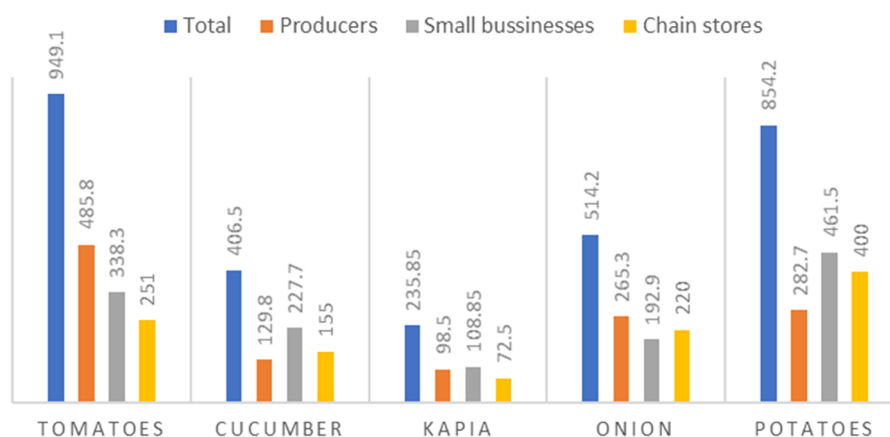


Fig. 4. Distribution of vegetable sales at Tulcea (annual, in tons).

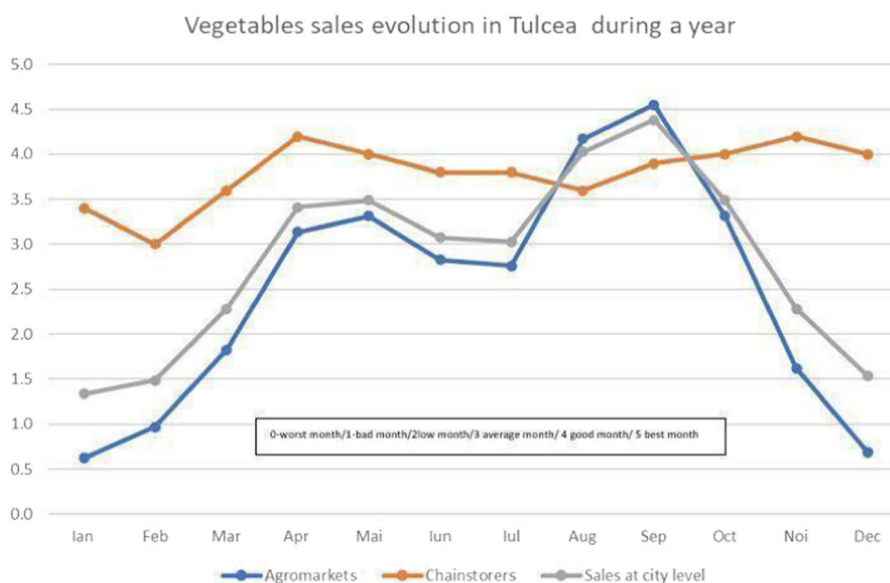


Fig. 5. Annual distribution of vegetable sales in Tulcea.

city-wide reflect the producers' lack of greenhouses, which could facilitate year-round production. These results are consistent with information obtained during earlier phases of the project, which revealed that local vegetable producers can supply the market in spring and autumn at the moment but have a hard time competing with chain grocery stores throughout the rest of the year.

The five selected vegetables sold in Tulcea vary considerably according to their reported origin location (Fig. 6). Kapia peppers and onions are predominantly produced in the county surrounding Tulcea city (Tulcea county), with some produced in other Romanian counties, and the remainder imported from outside Romania. By contrast, the majority of cucumbers and tomatoes sold in Tulcea city are imported. Potatoes are largely imported or produced elsewhere in Romania.

The origin of vegetables produced in Tulcea county can be further traced to smaller jurisdictions, including the Tulcea Administrative Territorial Unit (ATU), the Sarichioi ATU, the Valea Nucarilor ATU, and other localities (Fig. 7). Of the five vegetables studied here, only cucumbers were largely produced within the Tulcea ATU (55 %). The other four vegetables were produced almost exclusively in other jurisdictions besides Tulcea ATU.

This analysis reveals that local producers supply only a small proportion of the market demand for the five vegetables examined here. The

supply instead originates largely from imports or locations outside of Tulcea county, increasing the energy and associated environmental impacts of local vegetable consumption (Paxton, 1994).

During the interviews, respondents acknowledged the importance of fuel consumption due to the source location of food as an important FWE nexus consideration for promoting a sustainable food system in Tulcea. Indeed, some respondents noted that they found it hard to promote local products or provide a competitive price due to high production expenses, transport costs, and taxes.

3.4. Other local concerns

Finally, the interview questionnaire asked about problems facing local vegetable producers and retailers of different sizes and which measures would be useful to be taken by authorities (Fig. 8). While many respondents did not answer, those who did respond identified needs for improved infrastructure and parking, renovating agro-markets, irrigation, grants and project funds, as well as a handful of other items. These results are consistent with findings from earlier phases of the research (interviews, workshops) that limited infrastructure and high irrigation and electricity costs represent persistent problems for producers.

Origin of vegetables sold in Tulcea

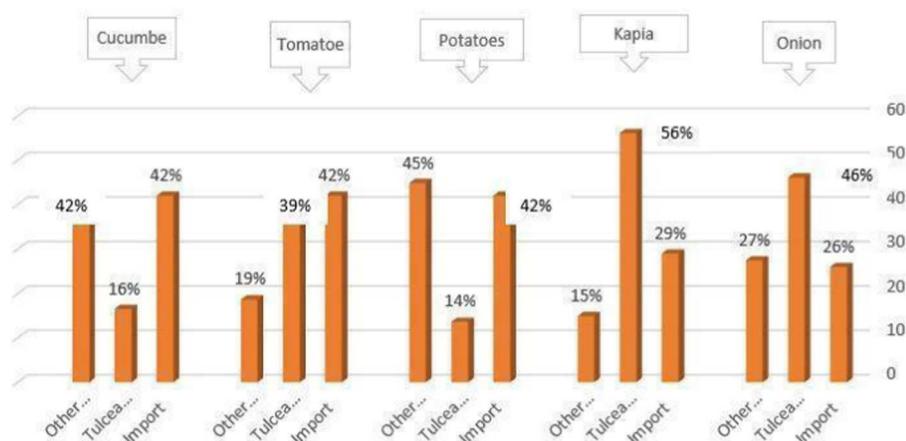


Fig. 6. Origin of vegetables sold in Tulcea.

The origin of vegetables produced in Tulcea County

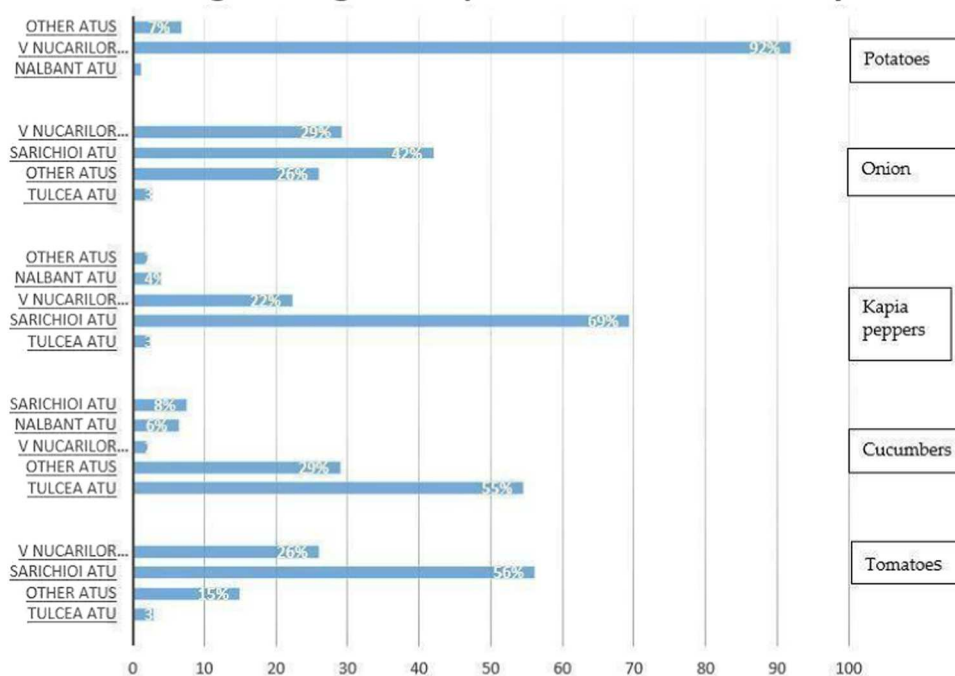


Fig. 7. Origin of vegetables produced in Tulcea County.

3.5. Usability of the Tulcea tool

Results of the illustrative vegetable market analysis were presented along with the final tool to stakeholders at an online workshop in October 2020 (Section 2.2.4). Participants then completed an anonymous usability survey, which asked questions about usefulness, attractiveness, innovativeness, and ease of use.

Despite the few responses, the results from the 15 workshop participants are informative. For instance, when questioned about the attractiveness of the information provided in the tool, 46 % of respondents considered the interactive map to be the main attraction, while 23 % were attracted by the promotion of local producers, and the remaining responses noted different aspects of the tool as being attractive.

When asked about other functionalities that could be added to the tool, respondents suggested the addition of other energy sources besides electricity (i.e., natural gas), the possibility to add images, and the possibility to give ratings of the providers. All suggestions have been

documented although, since this project has now been completed, further tool development will depend on action by the local authorities.

4. Discussion and conclusions

The Tulcea case study illustrates FWE nexus as a complex and dynamic system. Our results suggest that using participatory research methods in the FWE nexus research help generate new knowledge and capacity for integrating the FWE nexus thinking into sustainable local governance. The process involved multiple phases of data collection, including key informant interviews about the FWE nexus and its interconnections, and a series of public workshops with participatory approaches. Engaging different stakeholders, including citizens and representatives of public and private sector organizations in the research process increased the local relevance of this study and promoted cooperation and collaboration. Participatory research methods and iterative feedback process helped to improve the Tulcea tool as a decision-support

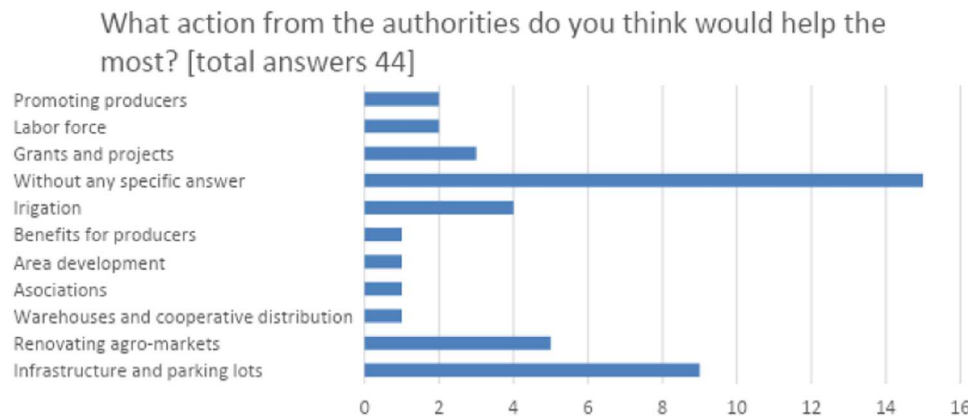


Fig. 8. Graphic representing problems identified among producers and traders.

tool for tackling food sustainability issues in Tulcea and to link local producers and consumers. The tool was tailored to the specific needs of the local stakeholders in Tulcea and then used to characterize the local vegetable market and its connections to water and energy. Taken together, the process enabled social learning about the nexus and possible solutions, as prioritized by nexus and sustainability scholars.

The research confirmed the importance of continuously working with local stakeholders when developing a nexus solution. Involving multiple local stakeholders helped to adjust the initial research focus from water to food, as a locally-relevant entry point for discussing FWE nexus challenges. Based on the stakeholder input, the initial goal of the research team to focus on the water system as a key FWE nexus component (i.e., irrigation in the Zaghen Lake area) shifted to improving the local food system, which was more tangible and aligned better with local needs, as found in other FWE nexus studies. While irrigation cost, infrastructure and energy sources present problems for local producers, they generally expressed more interest in finding a solution for enhanced visibility and representation of their products in the local market, thus connecting the FWE nexus conversation directly to livelihoods.

Our analysis of the local vegetable market showed that local producers comprise a small proportion of the market. The demand for vegetables in Tulcea is currently met by producers from other territorial administrative units in Tulcea County, other counties or other countries (50 % of vegetables are imported) resulting in high energy cost. This project established local interest in optimizing energy use and environmental protection by reducing food transport distances, optimizing water use for irrigation, and reducing the quantity of imported food. Such interest could translate into support for local sustainable development initiatives (especially for SDG11, Sustainable Cities and Communities) (Bleischwitz et al., 2018).

Another key finding is that local producers in Tulcea find it difficult to promote their products to consumers and sometimes they cannot give a competitive price due to production expenses, transport and taxes. This result was discussed with stakeholders (e.g. city administration, retailers) and will be further considered by the local governance actors in the FWE integration. Improved visibility of local products, if influencing product supply decisions, could ultimately contribute to a more sustainable food system in Tulcea. Purchasing locally-produced food means more financial support for the local economy, promoting community cohesion while reducing food mileage (Paxton, 1994) and ensuring the freshness of products (Endo et al., 2017). Improved utilization of locally available FWE resources could also increase local resilience to supply disruptions while improving trade, foreign investment, and resource conservation and efficiency (Mohtar et al., 2015).

Our study results, in combination with the Tulcea Tool, as a decision support tool for FWE nexus thinking, offers local producers a strategic approach, taking into account the consumer profile, energy usage and environmental impact information. Tulcea tool has potential to provide ongoing support for the integration of the FWE system into local

governance, towards a balanced sustainable development. Use of the Tulcea tool by a large number of local stakeholders can raise awareness about the connections between food, water and energy, and the potential impacts on the environment. Additionally, the Tulcea tool connects consumers with small local producers, allowing them to promote their products and locations, thus increasing the resilience of the local food system. Analyzing the data collected from the consumer profile, food producers could gradually adapt to the requirements of the local market, taking into consideration water-energy interlinkages and influences (distances, energy use, environment) and consumer preferences. While the ecological footprint of imported vegetables was not included in this study, it can be included in future research for a more comprehensive understanding of sustainable food systems at the regional scale.

Future research could also involve further development of the Tulcea tool to incorporate user feedback, add other nexus and sustainability indicators, and facilitate analysis of the data, creating a robust decision-support tool. While the tool is no longer being actively developed, users still have the opportunity to submit data, and future research could review the incoming data for new insights into producer or consumer preferences and opportunities for supply chain improvements. Such applied analysis could meaningfully support decision-making in Tulcea, especially by local governmental organizations with the authority and resources to invest in FWE resource infrastructures such as irrigation and upgrading agro-markets.

The COVID-19 pandemic affected the project by limiting the conduct of planned in-person interviews and workshops. The tool testing phase, for instance, was conducted almost exclusively under social distancing protocols and thus online. We recognize the difficulties of engaging inclusively with diverse stakeholder groups across the digital divide (Laborgne et al., 2021b). While the project team had already built many relationships with stakeholders before the pandemic, facilitating trust and enabling access, engagement of new stakeholders during the testing and final presentation phases was challenging.

Author Contributions

Dragoş Balaican: conceptualization, investigation, writing—original draft and editing, Final review. **Iulian Nichersu:** conceptualization, methodology, funding acquisition, supervision, resources. **Iuliana. I. Nichersu:** conceptualization, writing—original draft and editing. **Andrea Pierce:** writing—review and editing, methodology, conceptualization, Final review. **Olga Wilhelmi:** writing—review and editing, methodology, conceptualization, Final review. **Pia Laborgne:** writing—review and editing, methodology, conceptualization. **Edward Bratfanof:** investigation, conceptualization.

Funding

This study was supported by the Sustainable Global Urban Initiative

(SUGI) Food-Water-Energy Nexus program. This program has been set up by the Belmont Forum and the Joint Programming Initiative (JPI) Urban Europe and has received funding from the European Union's Horizon, 2020 research and innovation program under grant agreement # 730254 and the following national funding agencies: the Executive Agency for Higher Education, Research, Development and Innovation (UEFISCDI), of Romania funded this work under grant #COFUND-ERANET-ENSUGI-Creating Interfaces, the U.S. National Science Foundation (NSF) funded this work under grant #1830933, the German Federal Ministry of Education and Research (BMBF) funded this work under grant # 01UV1803A..

Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Data availability

Data will be made available on request.

Acknowledgments

For the implementation of the activities of data collection, together with the authors contributed the entire DDNI Creating Interfaces Project Team.

References

- Al-Ansari, T., Korre, A., Nie, Z., Shah, N., 2015. Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus. *Sustain. Prod. Consumpt.* vol. 2, 52–66. <https://doi.org/10.1016/j.spc.2015.07.005>.
- Al-Riffai, P., Breisinger, C., Mondal, A.H., Ringler, C., Wiebelt, M., Zhu, T., 2017. Linking the Economics of Water, Energy, and Food: A Nexus Modeling Approach (in). Egypt SSP. <https://doi.org/10.13140/RG.2.2.14026.16321>.
- Apetrei, C.I., Caniglia, G., von Wehrden, H., Lang, D.J., 2021. Just another buzzword? A systematic literature review of knowledge-related concepts in sustainability science. *Glob. Environ. Change* 55.
- Artioli, F., Acuto, M., McArthur, J., 2017. The water-energy-food nexus: an integration agenda and implications for urban governance. *Pol. Geogr.* 215–223.
- Bleischwitz, R., Spataru, C., VanDeveer, S.D., Obersteiner, M., van der Voet, E., Johnson, C., Andrews Speed, P., Boersma, T., Hoff, H., van Vuuren, D.P., 2018. Resource nexus perspectives towards the united nations sustainable development goals. *Nat. Sustain.* vol. 1, 737–743. <https://doi.org/10.1038/s41893-018-0173-2>.
- Caniglia, G., Luederitz, C., von Wirth, T., Fazey, I., Martín-López, B., Hondra, K., König, A., von Wehrden, H., Schöpke, N., Laubichler, M., Lang, D., 2020. A pluralistic and integrated approach to action-oriented knowledge for sustainability. *Nat. Sustain.* 10–15.
- Cronje, R., Rohlinger, S., Crall, A., Newman, G., 2011. Does participation in citizen science improve scientific literacy? A study to compare assessment methods. *Appl. Environ. Educ. Commun.* 135–145. <https://doi.org/10.1080/1533015X.2011.603611>.
- Endo, A., Tsurita, I., Burnett, K., Orenco, P.M., 2017. A review of the current state of research on the water, energy, and food nexus. *J. Hydrol. Reg. Stud.* 11, 20–30. <https://doi.org/10.1016/j.ejrh.2015.11.010>.
- Fan, J.-L., Kong, L.-S., Zhang, X., 2018. Synergistic effects of water and climate policy on energy-water nexus in China: a computable general equilibrium analysis. *Energy Policy* 123, 308–317. <https://doi.org/10.1016/j.enpol.2018.09.002>.
- FAO, 2014. The Water-Energy-Food Nexus. A New Approach in Support of Food Security and Sustainable Agriculture. FAO, Rome, Italy.
- EIFER I European Institute for Energy Research/EIFER I European Institute for Energy Research, "Creating Interfaces project," EIFER, 2020. [Online]. Available: (<https://creatinginterfaces.eifer.kit.edu/project/>). [Accessed 15 12 2020].
- Fang, D., Chen, B., 2017. Linkage analysis for the water-energy nexus of city. *Appl. Energy* vol. 189, 770–779. <https://doi.org/10.1016/j.apenergy.2016.04.020>.
- Feng, K., Hubacek, K., Siu, L.Y., Li, X., 2017. The energy and water nexus in Chinese electricity production: A hybrid life cycle analysis. *Renew. Sustain. Energy Rev.* 39. <https://doi.org/10.1016/j.rser.2014.07.080>, pp. 342–335.
- Frantzeskaki, N., Broto, V.C., Coenen, L., Loorbach, D., 2019. *Urban Sustainability Transitions*. ISBN 9780367219086. Routledge.
- H. Hoff, "Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm,," Bonn 2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute, Stockholm, p. 5, 2011.
- Jacobi, J., Mukhovi, S., Llanque, A., Giger, M., Bessa, A., Golay, C., Speranza, C.I., Mwangi, V., Augstburger, H., Buerger-Bonomini, E., Haller, T., Kiteme, B.P., Delgado Burgoa, J.M.F., Tribaldos, T., Rist, S., 2020. A new understanding and evaluation of food sustainability in six different food systems in Kenya and Bolivia. *Sci. Rep.* <https://doi.org/10.1038/s41598-020-76284-y>.
- Jalilov, S.M., Reskinen, M., Varis, O., Amer, S., Ward, F.A., 2016. Managing the water-energy-food nexus: gains and losses from new water development in Amu Darya River Basin. *J. Hydrol.* 539, 648–661. <https://doi.org/10.1016/j.jhydrol.2016.05.071>.
- Johnson, O.W., Karberg, L., 2017. Co-exploring the water-energy-food nexus: facilitating dialogue through participatory scenario building. *Environ. Sci.* <https://doi.org/10.3389/fenvs.2017.00024>.
- Jones, J.L., White, D., 2022. Understanding barriers to collaborative governance for the food-energy-water nexus: the case of Phoenix, Arizona. *Environ. Sci. Policy* vol. 127, 111–119.
- P. Laborgne, W. Goszczynski, M. Heyder, A. Sarzynski, K. Slebiada, J. Suchomska and J. Wendel, "Creating Interfaces: Knowledge co-creation and Participation in Urban Food-Water-Energy Nexus Governance," in SSPCR conference, Bolzano, Italy., 2019.
- Laborgne, P., Ekkile, E., Wendel, J., Pierce, A., Heyder, M., Suchomska, J., Nichersu, I., Balaican, D., Slebiada, K., Wroblewski, M., Goszczynski, W., 2021a. Urban Living Labs: how to enable inclusive transdisciplinary research? no. <https://urbantransformations.biomedcentral.com/articles/10.1186/s42854-021-00026-0> Urban Transform. no. <https://urbantransformations.biomedcentral.com/articles/10.1186/s42854-021-00026-0>.
- Laborgne, P., Ekkile, E., Wendel, J., Pierce, A., Heyder, M., Suchomska, J., Nichersu, I., Balaican, D., Slebiada, K., Wroblewski, M., Goszczynski, W., 2021b. Urban Living Labs: how to enable inclusive transdisciplinary research? no. <https://urbantransformations.biomedcentral.com/articles/10.1186/s42854-021-00026-0> Urban Transform. 3, 11.
- Lehmann, S., 2018. Implementing the Urban Nexus approach for improved resource-efficiency of developing cities in Southeast-Asia. *City, Cult. Soc.* 46–56.
- McCallum, I., Montzka, C., Bayat, B., Kollet, S., Kolotii, A., Kussul, N., Lavreniuk, M., Lehmann, A., Maso, J., Mazzetti, P., Mosnier, A., Perracchione, E., Putti, M., Santoro, M., Serral, I., Shumilo, L., Spengler, D., Fritz, S., 2020. Developing food, water and energy nexus workflows. *Int. J. Digit. Earth* vol. 13 (2), 299–308. <https://doi.org/10.1080/17538947.2019.1626921>.
- Menny, M., Palgan, Y.V., McCormick, K., 2018. Urban Living Labs and the Role of Users in Co-Creation. *GAIA - Ecol. Perspect. Sci. Soc.* 69–77.
- R.H. Mohtar, A.T. Assi and B. dAHER, "Bridging the Water and Food Gap: The Role of the Water-Energy-Food Nexus," in UNU-FLORES Working Paper Series 5, Edited by Hiroshan Hettiarachchi. Dresden: United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), 2015.
- Newell, J.P., Goldstein, B., Foster, A., 2019. A 40-year review of food-energy-water nexus literature and its application to the urban scale. *Environ. Res. Lett.* 14.
- Notarnicola, B., Serenella, S., Assumpcio, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. *J. Clean. Prod.* vol. 140, 399–409. <https://doi.org/10.1016/j.jclepro.2016.06.071>.
- Paxton, A., 1994. *The Food Miles Report: The dangers of long-distance food transport*. SAFE Alliance, London, UK.
- Salmoral, G., Yan, X., 2018. Food-energy-water nexus: a life cycle analysis on virtual water and embodied energy in food consumption in the Tamar catchment, UK. *Resour. Conserv. Recycl.* vol. 133, 320–330. <https://doi.org/10.1016/j.resconrec.2018.01.018>.
- Seidel, C., 2016. The application of life cycle assessment to public policy development. *Int. J. Life Cycle Assess.* vol. 21, 337–348. <https://doi.org/10.1007/s11367-015-1024-2>.
- S.A. Sheppard, " <https://wq.io>," 26 11 2020. [Online]. Available: (<https://wq.io>).
- Shi, H., Ji, C., Suning, L., Bellie, S., 2019. The role of large dams in promoting economic development under the pressure of population growth. *Sustainability* 11, 11. <https://doi.org/10.3390/su11102965>.
- Stollnberger, R., Gebetsroither-Geringer, E., Magerl, U., 2020. Integrated Qualitative and Quantitative Analysis of Causal Urban Food-Water-Energy Relations towards more Climate-Resilient Cities. REAL CORP. ISBN 978-3-9504173-8-8 (CD), 978-3-9504173-9-5, 2020.
- Tulcea County Directorate of Statistics/Tulcea County Directorate of Statistics, "INSSE. RO," 2022. [Online]. Available: (<https://tulcea.insse.ro/produse-si-servicii/sta-tistici-judetene/populatia/>).
- Tye, M., Wilhelm, O., Pierce, A., Sharma, S., Nichersu, I., Wroblewski, M., Goszczynski, W., Wendel, J., Laborgne, P., Heyder, M., Nichersu, I., 2022. The food water energy nexus in an urban context: connecting theory and practice for nexus governance. *Earth Syst. Gov.* 12. <https://doi.org/10.1016/j.esg.2022.100143>.
- Vaughn, L., Jacques, F., 2020. Participatory research methods – choice points in the research process. *J. Participatory Res. Methods* 1. <https://doi.org/10.35844/001c.13244>.
- Wahl, D., Ness, B., Wamsler, C., 2021. Implementing the urban food-water-energy nexus through urban laboratories: a systematic literature review. *Sustain. Sci.* vol. 16, 663–676. <https://doi.org/10.1007/s11625-020-00893-9>.
- Wittwer, G., 2010. The economic impacts of a new dam in South-East Queensland. *Aust. Econ. Rev.* 42, 12–23. <https://doi.org/10.1111/j.1467-8462.2009.00506.x>.
- Wu, X.D., Chen, G.Q., 2017. Energy and water nexus in power generation: the surprisingly high amount of industrial water use induced by solar power infrastructure in China. *Appl. Energy* vol. 195, 125–136. <https://doi.org/10.1016/j.apenergy.2017.03.029>.
- Yan, W., Roggema, R., 2019. Developing a design-led approach for the food-energy-water nexus in cities. *Urban Plan.* 4, 123–138.