Quantitative Storytelling: Science, narratives and uncertainty in nexus innovations

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Abstract

Innovations are central instruments of sustainability policies. They project future visions onto technological solutions, and enable win-win framings of complex sustainability issues. Yet, they also create new problems by interconnecting different resources such as water, food and energy, what is known as the "WEF nexus." In this paper, we apply a new approach called Quantitative Storytelling (QST) to the assessment of four innovations with a strong nexus component in EU policy: biofuels, shale gas, electric vehicles, and alternative water resources. Recognizing irreducible pluralism and uncertainties, QST inspects the relationships between the narratives used to frame sustainability issues and the evidence on those issues. Our experiences outlined two rationales for implementing QST. First, QST can be used to question dominant narratives that promote certain innovations despite evidence against their effectiveness. Second, QST can offer avenues for pluralistic processes of co-creation of alternative narratives and imaginaries. We reflect on the implementation of QST and on the role played by different uncertainties throughout these processes. Our experiences suggest that while the role of nexus assessments using both numbers and narratives may not be instrumental in directly inducing policy change, they are valuable means to open discussions on innovations outside of dominant nexus imaginaries.

Keywords: narratives, innovations, WEF nexus, complexity, uncertainty

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1 Introduction

The analysis of sustainability challenges in complex social-ecological systems calls for the integration of multiple analytical methods, frames, and perspectives. The EU Horizon 2020 project MAGIC, short for Moving Towards Adaptive Governance in Complexity: Informing Nexus Security, investigates the relationships between nexus elements of social-ecological systems, such as water, energy and food, and the narratives that are used to frame those relationships and systems (Ripa and Giampietro 2017). To do so, MAGIC combines quantitative analyses, qualitative analyses, and the engagement of different actors, through a transdisciplinary approach called Quantitative Storytelling (QST). QST was proposed to address gaps in the science for governance literature with respect to complexity and uncertainty as ground principles for knowledge co-production (Saltelli and Giampietro 2017). By recognizing the irreducible plurality of complex reality and the inevitable existence of uncertainties, QST aims to check the coherence between the narratives used to frame sustainability issues tied to nexus dimensions and the evidence on those issues, where the evidence can be already existing, or newly produced by QST researchers**.** In this paper, we reflect on our shared experiences of using the QST approach in assessing the narratives underpinning innovations for sustainability, focusing on four innovations that have a strong nexus component: alternative water resources, biofuels, shale gas and electric vehicles.

The concept of the water–energy–food nexus was popularized following the Bonn 2011 Nexus Conference, in response to climate change and social changes including population growth, globalization, economic growth and urbanization (Hoff 2011). A nexus lens emphasizes the complex relationships between water, energy, and food (Harwood 2018). Grounded in a holistic, systems perspective, critical nexus assessments can highlight the inherent trade-offs between sustainability dimensions, showing how decisions taken in one sector of the nexus may have direct or indirect consequences on other sectors (van Gevelt 2020). However, discourses of future pathways can also take

the form of nexus imaginaries. In this case, a specific solution, often in the form of innovation, is expected to simultaneously solve problems across multiple nexus dimensions (Cairns and Krzywoszynska 2016; Pfotenhauer and Jasanoff 2017). These win-win framings assume that consequences of complex policy decisions can be mapped onto binary outcomes, generating either winners or losers (Jasanoff 2007). Focusing on the science-policy-society interface, (Urbinatti et al. 2020) introduce the "nexus of humility" framework. Humility is associated with irreducible uncertainty and epistemic pluralism. In this view, the nexus shifts from being a problem to be solved, to being a way of viewing problems. Following this view, in this paper and in the QST process developed within the MAGIC project we open our nexus focus from an object-oriented one (i.e., the nexus as a set of material relationships between water, energy and food) to a relational one (i.e., the nexus as an entangled set of relationships between different observers and complex reality). This view includes different actors, values, and imaginaries within nexus relationships.

In this paper, we focus on nexus innovations in the European policy context. Since innovations are future-oriented, actors cannot predict-then-act from an evidence base (Borup et al. 2006). Faced with complex issues and incomplete knowledge, they must rely on narratives, expectations, and imaginaries to avoid paralysis. Our definition of narrative is conceptually grounded in complexity (Zellmer, Allen, and Kesseboehmer 2006) and in post-normal science (Funtowicz and Ravetz 1993). Complexity arises from system-observer relationships: representations of complex situations cannot be compressed into a single, self-consistent view. This entails impredicativity, with events unfolding and simultaneously affecting one another at different scales. As such, there is no unique direction of causality in complex systems (Mitchell 2002). For example, innovations affect and are affected by behaviors, like in the chicken-egg paradox. To allow for decision-making in impredicative situations, narratives are used to simplify reality by fitting it within a chosen (causal) storyline. When narratives are projected onto the future, they become expectations, i.e., "future-oriented abstractions," smoothing uncertainties to provide a shared vision that different actors can act upon (Borup et al. 2006).

Narratives and expectations are constructed within sociotechnical imaginaries, i.e., collectively held social beliefs and values defining what is

desirable (Jasanoff and Kim 2015). Impredicativity is also present in the narrative-imaginary relationship: on one hand, narratives are grounded in imaginaries; on the other, they can reinforce those imaginaries, or create and perform new ones. As with the chicken-egg paradox, it is impossible to say whether a narrative or an imaginary came first, as they co-create one another across different timescales. Imaginaries help explain why, out of the universe of possibilities, some visions of techno-scientific and social order win support over others, reducing the indeterminacy of the future. Actors may choose to view complex sustainability challenges using different narratives, grounded in their own imaginaries and expectations. This generates a plurality of voices and values (Jasanoff 2007; Allen and Giampietro 2006). To handle this plurality, scientific knowledge must actively deal with the uncertainty associated with the existence of diverse narratives. By recognizing multiple (and often contradictory) legitimate perspectives, the attention of QST is placed on how innovations are framed, what evidence is used to support them, and how evidence and narratives interact. Throughout the process, the role played by different types of uncertainties in science-policy relations is observed.

In the rest of this paper, we present a meta-analysis of four case studies carried out within the MAGIC project, looking at the narratives behind alternative water resources, electric vehicles, biofuels, and shale gas within European contexts. Each case study was developed by applying the QST approach to discuss the role played by those innovations in solving complex sustainability problems. Details on individual case studies can be found in Cabello et al. (2020, 2021) for alternative water resources; Di Felice et al. (2020) and Di Felice, Renner, and Giampietro (2021) for electric vehicles; Cadillo-Benalcazar et al. (2020) and Ripa, Cadillo-Benalcazar, and Giampietro (2021) for biofuels and Madrid Lopez (2020) for shale gas. By exploring the commonalities and differences of the case studies, we re-frame QST as a tool to navigate and inspect science-policy relations, using our experiences to reflect on the interactions between scientific assessments, plural narratives, and uncertainty in the governance of nexus innovations.

2 Quantitative Storytelling, Narratives & Uncertainty

QST was developed within MAGIC as a common methodological ground for transdisciplinary nexus research (Matthews et al. 2017). It builds and expands on the accounting scheme known as MuSIASEM (Multi-Scale Analysis of Societal and Ecological Metabolism), developed prior to QST for quantitative accounting of the nexus across scales (Giampietro, Mayumi, and Ramos-Martin 2009; Giampietro et al. 2014). MuSIASEM is grounded in bio-economics, complexity, and hierarchy theory. It contributes to system perspectives of sustainability issues, by describing social-ecological systems across hierarchical levels, geographical and temporal scales. MuSIASEM is characterized by a focus on the relations among nexus variables -- how water, food, energy, land, GHG emissions, labor, etc. are interlinked in social-ecological processes at different analytical levels. Complexity in system-observer relationships means that situations can be viewed differently depending on how a problem is framed and analyzed, and by whom (Rosen 1991; Kovacic and Giampietro 2015). The way actors choose to frame and address reality builds on their narratives, which cannot be true or false. In this context, MuSIASEM does not aim to generate quantitative assessments that are true or correct, but ones which are coherent at a given point in time, by linking numbers and variables across scales and levels (what is also known as the “Sudoku effect” (Giampietro and Bukkens 2015)). To do so, MuSIASEM accounts for the inputs and outputs associated with processes at a chosen scale of analysis (e.g., the amount of water consumed, and greenhouse gases emitted by a power plant) and aggregates those processes for higher-scale, contextualized descriptions (e.g., the amount of water consumed, and greenhouse gases emitted by the electricity sector of a country, in a given year). For more details on MuSIASEM, see (Giampietro et al. 2014).

QST broadens MuSIASEM to include coherence not only between numbers at different levels and scales, but also between numbers and the narratives they build on. This leads to a shift from MuSIASEM’s goal of generating coherent quantitative assessments, to a wider goal in QST of generating assessments that are fit for purpose (i.e., adequate in addressing desired concerns) (Funtowicz and Ravetz 1990). For example, if the concern is ensuring security of energy supply in a country, MuSIASEM builds a coherent analysis by breaking down the country into its different regions, sectors into sub-sectors, and linking energy production and consumption patterns with other nexus dimensions. With a broader scope,

QST would add phases of qualitative analysis and/or public interaction to answer questions such as: Why is security important, and to whom is it important? What untold stories are associated with official security narratives?

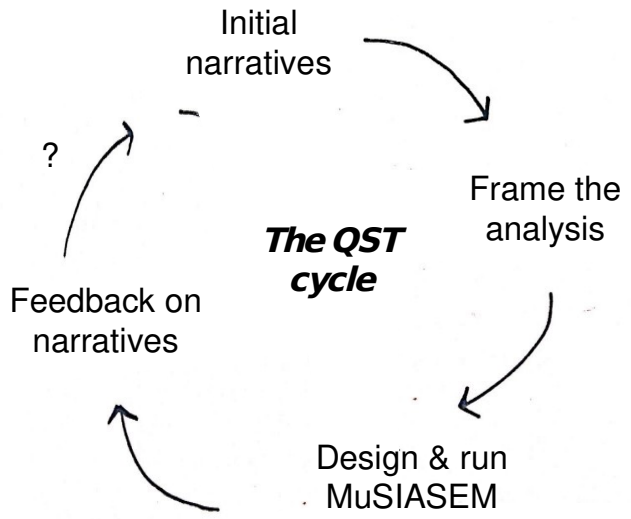

Figure 1. Initial QST cycle

Figure 1 shows the initial conceptualization of QST as an iterative cycle, with a quantitative part and a qualitative one (characterized by the analysis of narratives). At the start of the cycle, narratives relevant to a given innovation are identified. From those narratives, nexus problems to be explored are framed. A MuSIASEM analysis is then designed and executed. The information produced by the quantitative analysis is then interpreted, feeding back into the pool of narratives on the topic. QST allows for each step to be developed in different ways, depending on the purpose of the cycle. This is due both to the openness of the approach, and to the fact that it is still new, and thus not rigorously formalized. Engagement activities can be used at any stage of the QST process: to identify narratives, to design the quantitative assessment or to interpret and discuss results. Crucially, actors are involved in the final stage of sharing and validating analytical feedback. If the narratives are taken from interviews with policymakers, for example, the QST cycle ideally closes by presenting those policymakers with information, leading to the emergence of a different set of narratives in relation to the problem at hand.

To understand concerns around innovations and the problems they are supposed to address, we distinguish between three types of interrelated policy narratives to start the cycle, which can be identified either through direct interviews with relevant actors, or through text analyses of policy documents (or both): justification narratives, normative narratives, and explanation narratives (Giampietro 2018). Normative narratives answer the question: “What should be done?” Justification narratives operate at a higher level of abstraction, answering the question: “Why should it be done?” They identify relevant concerns to be addressed and relate them with solutions and normative goals. In doing so, they create expectations for the performance of those solutions. Explanation narratives operate at a lower abstraction level, answering the question: “How should it be done?” They specify the conditions under which those goals should be pursued. This taxonomy is useful in mapping relations among policy narratives, but it does not carry information about who the narrative is generated by, and for what purpose. To include this positionality dimension, we follow the distinction between dominant and alternative imaginaries used by (Longhurst and Chilvers 2019), translating it into dominant and alternative narratives. In this logic, dominant narratives are those generated within centers of power. These centers could be government institutions, academic ones, lobbies, etc. There can be contrasting dominant narratives at different governance levels, e.g., EU narratives versus those of a local government. Alternative narratives are decentralized ones, generated outside of these centers of power. This distinction, which is dependent on levels of governance, is useful when discussing the possible impacts of scientific assessments. The original goal of QST was one of falsification of dominant innovation narratives, using multi-scale nexus assessments to show how these narratives are not necessarily grounded in biophysical reality. In this context, the aim was to substitute dominant innovation narratives with a set of alternative ones which are more coherent across environmental and socio-technical dimensions and fit for the concerns they are meant to address. This goal, however, had important limitations as it viewed innovations as purely material, rather than political, objects. We will reflect on this in Sections 4 and 5.

As mentioned in the Introduction, QST also recognizes that uncertainty is inevitable in the processes of knowledge production and decision-making. Following the work of (Knight 1921), (Wynne 1992), and (Stirling 2003),

uncertainty can be further split into the concepts of risk, strict uncertainty, ignorance, indeterminacy and ambiguity. With risk, the odds are known; in strict uncertainty, unknowns are known; in ignorance, unknowns are unknown. Indeterminacy and ambiguity are irreducible properties of complexity: the former refers to the fact that complex systems are characterized by open causal chains, while the latter refers to the irreducibility of plural perspectives (Kovacic and Di Felice 2019). The functionality of ambiguity in decision-making processes has been long acknowledged. In the policy realm, (Matland 1995) first made the distinction between ambiguity of means (plural explanation narratives) and ambiguity of goals (plural normative narratives), each being functional in order to reach policy decisions. There is also ambiguity in the problem framing (plural justification narratives) when actors have different understandings and underlying assumptions on what the problem is, and why it is a problem (Brugnach and Ingram 2012). Henry Kissinger referred to “constructive ambiguity” as the “deliberate use of ambiguous language in a sensitive issue in order to advance some political purpose” (Berridge and James 2003, 51). However, recognizing our grounding in complexity, it is important here to make the distinction between vagueness and ambiguity (Kovacic and Di Felice 2019). The former refers to lack of clarity when using a term (so constructive ambiguity, to us, falls under vagueness) and is a political choice. For example, the statement that oil imports to the EU are from politically unstable regions (EC 2013) is vague, as it purposefully does not name these regions. Ambiguity, on the other hand, has a wider scope as it refers to incommensurability. The concept of energy security is ambiguous not because it lacks clarity, but because multiple definitions of energy security can co-exist. This distinction is relevant to the case studies presented below.

3 Applications of QST

This paper draws on four case studies assessing innovations with QST in the MAGIC project: biofuels, shale gas, electric vehicles, and alternative water resources (Boxes 1-4). The innovations were chosen due to their relations with the nexus elements of water, food, energy and climate. In this section, we briefly describe the main characteristics of each case study (Table 1) and discuss commonalities and differences with regards to their purpose, methods, and results.

BOX 1 - Biofuels as an example of the climate-energy-food nexus in the EU.

Innovation: Biofuels refer to liquid fuels for transport produced from biomass (EC 2018, 104). The technological development of this innovation can be defined as mature for first generation biofuels, i.e., food crops biofuels, and emerging for advanced biofuels, i.e., biofuels produced from various types of non-food biomass, as some of them are still at a non-commercial stage (Cheng and Timilsina 2011).

Nexus relevance: The production of biofuels can be intuitively linked to multiple nexus dimensions, such as the competition of first generation biofuels with food for land and water; and the energetic and economic convenience of advanced biofuels.

European policies: Policies for biofuels and advanced biofuels have been in place since 2003 with the biofuels directive (Directive 2003/30/EC). The revised Renewable Energy Directive (REDII) (2018) introduced a 14% RES-transportation energy target and a 3.5% advanced biofuels sub-target by 2030 (EC 2018).

BOX 2 - Shale gas as an example of the water-energy nexus in the EU.

Innovation: Shale gas is an unconventional source of natural gas held in shale stone pores. Its exploitation increases the availability of natural gas. It is considered as a means to increase energy security and geopolitical power related to energy, and as a driver for rural development.

Nexus relevance: Shale gas is extracted with hydraulic fracturing or fracking, a technology that drills into the earth and injects a high-pressure mixture of waters and chemicals to fracture layers of shale stone, releasing gas. Thus, the process of fracking is deeply tied to impacts on water and land.

European policies: Following the U.S. experience and in preparation for a situation of severe natural gas supply shortage, the EU considered in the early 2010s if and how shale gas should be developed and a regulatory framework to guide a potential implementation of the innovation was built (EC 2014b). The EU Energy Roadmap 2050 sees shale gas as a potentially important new source of natural gas to support the energy transition (EC 2012).

BOX 3 - Electric vehicles as an example of the climate-energy nexus in the EU.

Innovation: Electric vehicles are an alternative to internal combustion engine vehicles (ICEVs), running on electric-powered batteries rather than fuel-powered engines. As such, they have little to no tailpipe emissions when compared to ICEVs.

Nexus relevance: While reducing tailpipe emissions, electric vehicles require electricity production to function. Depending on how electricity is produced, it ties to different nexus dimensions - renewable electricity, for example, requires considerable amounts of land, while most power plants consume large amounts of water. The GHG emissions of the manufacturing stage are also relevant to this innovation, and the GHG dimension is the most discussed in relation to electric vehicles.

European policies: Electric vehicles are a central measure in the EU's low-carbon transport strategy (EC 2013). Through the alternative fuel infrastructure directive, they are seen as a way to simultaneously reduce air pollution in cities, cut GHG emissions globally and increase security, while unlocking transport's potential to contribute to growth and jobs in the EU (EC 2014a).

BOX 4 - Alternative water resources as an example of the water-food-energy nexus in the Canary Islands.

Innovation: Desalination refers to the removal of dissolved salts in sea or brackish water to make it useful for drinking or irrigation. Reclamation adds a tertiary treatment to urban wastewater with the purpose of reducing concentrations of organic matter, pathogens, and different contaminants to acceptable levels for reuse.

Nexus relevance: Alternative water resources are commonly promoted in arid areas with intensive agricultural production as an effort to match

increasing water demands with available resources. Their production is energy demanding and increases water and food supply costs.

European policies: The Water Framework Directive (2000/60/EC) does not mention alternative water resources. However, they are fundamental innovations in water management strategies of southern Mediterranean regions. The Canary Islands was chosen as a case study because it pioneered the development of these technologies in the sixties and they are now central to their water and agricultural policies (Serrano-Tovar et al. 2019).

Following the QST goal of checking the coherence between narratives and evidence, all cases asked: Does the innovation fulfill its material expectations? And, what uncertainties surround the implementation of these innovations? In practice, the operationalization of QST across the four case studies followed two rationales. For biofuels and shale gas, the goal was to examine whether justifications of these innovations (persistent for biofuels, and newer for shale gas) are coherent from a biophysical, multi-scale perspective. Questioning justification narratives, these cases asked: Why should the EU produce biofuels and shale gas? For alternative water resources and electric vehicles, the analysis aimed at generating a collective reflection over the effectiveness of these innovations within a myriad of possibilities, questioning the dominant relationship between normative and justification narratives. We asked: What alternative imaginaries can be thought of around their implementation?

All cases started with an analysis of dominant narratives pertaining to the innovation. The analysis of biofuels addressed justification narratives through a historical analysis of EU directives (Cadillo-Benalcazar et al. 2021).[1] Over the years, biofuels have been proposed as a means to justify a set of continuously moving targets (mirroring Matland's "ambiguity of goals"). In the 1980s, bioethanol was seen as way to deal with surplus wine and grain production. More recently, biofuels justifications have been aligned with wider EU policy goals, namely to combat climate change, and to improve energy security. The quantitative analysis examined different constraints to current EU biofuel

1 The analyzed directives are: the Transport Biofuels Directive 2003/30/EC of 08 May 2003; Renewable Energy Directive 2009/28/EC from 23 April 2009 (in force); Fuel Quality Directive 2009/30/EC of 23 April 2009, amended 2016 (in force); ILUC Directive (EU) 2015/1513 of 9 September 2015 (in force); Renewable Energy Directive (recast) 2018/2001 of 11 December 2018 (in force).

production. First, an assessment of EU dependency to imports from other countries showed that a significant part of the feedstock used to produce biofuels in 2016 was imported from third countries (Cadillo-Benalcazar et al. 2021). In addition, those crops drive important land use changes with derived GHG emissions. These results compromise both energy security and climate change goals. Secondly, an in-depth national case study focused on The Netherlands as a major exporter of biofuels within the EU (Ripa, Cadillo-Benalcazar, and Giampietro 2021). The analysis quantified three scenarios for national production of feedstock and found severe land availability constraints. These quantitative exercises were used to question the mechanisms giving continuity to biofuels in EU policies. An engagement event with modelers and policy officers at the Energy Modeling Platform for Europe 2019 discussed the quality of biofuel policy narratives, taking our quantitative results as a starting point. Concerning energy security, both modelers and policy officials acknowledged the fact that biofuels cannot replace fossil fuels and questions of why such narratives keep playing an important role in EU energy discourses were raised.

The analysis of shale gas (Madrid Lopez 2020) inspected the coherence of the EU narrative that cautiously justifies this energy source as a way of increasing the chances of natural gas adoption as a “Plan B” for the transition to a clean energy system (EC 2014b). In practice, the QST process tested two sides of the narrative that were identified from a policy analysis paired with targeted interviews with key representatives of DG Energy, DG Environment, academics, the industry, and NGOs (Madrid Lopez 2020). The first claim was that shale gas could make up for the reduction of natural gas production resulting from the closing of the Dutch fields in order to meet EU gas demand by 2035. The second claim was that this increase in natural gas share will reduce the energy system’s GHG emissions and be able to respect the principles of the Water Framework Directive (WFD). A GIS model of shale gas exploitation was built for the EU, and MuSIASEM was applied to assess the metabolism of those wells with a regionalized and demographic perspective. First, well productivity was classified according to age and geological characteristics. Then, two scenarios were assessed in which drilling activity covered all potentially productive and non-protected land in the EU. The scenarios showed that shale gas production would not be enough to offset demand. GHG emissions would not be reduced, and

some shale gas activity would need to take place in river basins that are already under stress as defined by the WFD. Consequently, both sides of the narrative were falsified. Even with all potential land drilled, shale gas does not contribute significantly to improving security of energy supply, nor is it a ”clean” energy source as per the EU emission and water policy standards.

In these cases, what is relevant for the relationship between the evidence base and justification narratives is a high degree of ambiguity. In the biofuel case, the innovation is associated with highly ambiguous and ever-changing goals. The solution of biofuels persists over the years, while its justifications are updated depending on EU priorities (Cadillo-Benalcazar et al. 2021). Vagueness also has a part to play here (for example, when the Commission states that “Biofuel production should be sustainable” (EC 2009)). However, ambiguity in biofuel policy persists even when vagueness is cast aside. For example, despite specific targets set by type of biofuels (e.g., the maximum contribution of first-generation biofuels is limited to 7% of transport energy (EC 2018)), biofuels are still championed as a vehicle for ambiguous goals such as energy security. This persistence of justifications despite incongruences with biophysical reality has implications for the role and usefulness of quantitative assessments, as we will discuss in Section 4. In the shale gas case, the relative newness of the innovation (when compared with biofuels) leads to a different dynamic of dominant justifications. Shale gas, in fact, is too young to have a long history of evolving institutional narratives. Perceptions of shale gas have changed over time but also with governance levels. At the local level, shale gas development is promoted as a way to reach local development. At the national and supra-national level, shale gas is promoted as an essential component in achieving energy security. Ambiguity emerges at the level of justifications, as shale gas becomes a tool to reconcile local and national concerns. Unfortunately, in this case the planned workshop lost momentum due to loss of interest by energy policy officials, possibly due to the growing number of events aimed at discussing shale gas with policymakers.

Similar to shale gas, electric vehicles are a relatively new technology (in their current iteration). The analysis of electric vehicle narratives focused on the Clean Power for Transport Package (EC 2013). Justification narratives were identified from policy documents tied to the package and

categorized under four groups: environmental benefits, citizen wellbeing, energy security and economic benefits. For more details on which documents were analyzed and how the text analysis was carried out, see (Di Felice et al. 2020; Di Felice, Renner, and Giampietro 2021). The frequency of each justification narrative was tracked, showing how economic benefits are the most dominant justification used in relation to electric vehicles. On the quantitative side, data from existing studies and reports were used to check whether electric vehicles fulfill their expectations in the different justification domains. To do this, lifecycle assessments of different studies were compared, focusing on those that produced different results with respect to chosen narratives (e.g., studies predicting that electric vehicles reduce GHG emissions, and those predicting that they will increase GHG emissions). When inspecting the promises associated with electric vehicles, highly uncertain numbers were found. For example, it is unclear whether a shift to electric vehicles will create new jobs or lead to net job losses, and whether they will lead to substantial decreases in GHG emissions (Di Felice, Renner, and Giampietro 2021). In addition to this strict uncertainty, the analysis flagged the existence of ignorance and indeterminacy in assessing the evolution of future transport systems. For example, while there is incomplete knowledge about how many GHG emissions are associated with each step of the electric vehicle production process (known unknowns leading to strict uncertainty), there is also ignorance about the effects of the large-scale implementation of EVs on global emissions, and indeterminacy about how the technology and behaviors will co-evolve and interact (Di Felice, Renner, and Giampietro 2021). Two workshops with actors from regional co-operatives, urban planners and civil society aimed at discussing the justifications attached to electric vehicles and at imagining alternative sustainable transport futures (Di Felice et al. 2020). The uncertainties were used as an entry point to question the dominance of the electric vehicle solution and make space for alternative visions. Alternative imaginaries focused on the potential of public transport and car-sharing, discussing the challenges of a systemic transport transition. Consumer responsibility vs. government responsibility were discussed, and the winners and losers associated with the dominant techno-optimist imaginary were brought into the picture (Di Felice et al. 2020).

Narratives about alternative water resources were elicited through 27 interviews conducted by two MAGIC researchers to local actors in the Canary

Islands (Cabello et al. 2021). The actors were academics, practitioners, policymakers, and farmers with different knowledge on water, agriculture, and energy management. They highlighted win-win justifications for these innovations including security for farmers, agricultural sustainability, and lower pressures over groundwater. Expanding access to these resources was framed as the main governance challenge, generating expectations about positive benefits for new users. Against this backdrop, an analysis of water-crop supply patterns in a study area helped check the evidence on the multiple described roles of alternative water resources and to understand uncertainties associated with future expectations (Cabello et al. 2020, 2021). Contrary to the other innovations, alternative water resources in the Canaries had (partially) fulfilled their material promises. First, they were used by a variety of large exports-based and small locally oriented farms. Yet, they were mostly mixed with groundwater due to their high price. Second, aquifer levels had stabilized in recent years. However, there was strict uncertainty on how their dynamics had changed after decades of overdraft and ignorance on whether degraded groundwater quality could improve. On the other hand, the agricultural sector showed clear signs of regression (land abandonment, income reduction, decreasing number of farmers) due to interconnected local-global drivers. Therefore, it was implausible to anticipate the effect of expanding the access of alternative water resources to rural communities or new small farmers. Given the high energy demand of desalination and reclamation processes, variations in the electricity market posed serious risks to the economic viability of such water supply. These uncertainties were again used as a starting point for reflexivity in two engagement events with different actors, including public authorities, practitioners, farmers, and members of civil society. The focus of those events was the co-creation of new narratives: alternative futures with more sustainable agricultural practices were collectively imagined. The elements of such futures shifted the focus from water to agricultural governance, with fair prices and a relocalization of supply-consumption chains at its core. These two case studies illustrate how the inspection of uncertainties can guide plural conversations about the role of innovations in addressing complex sustainability issues.

Table 1 - Details of the application of QST to four case studies assessing nexus innovations

		Biofuels	Shale gas	Electric vehicles	Alternative water resources
REFERENCES		Cadillo-Benalcazar et al. 2021; M. Ripa, Cadillo-Benalcazar, and Giampietro 2021	Madrid Lopez 2020	Di Felice et al. 2020; Di Felice, Renner, and Giampietro 2021	Cabello et al. 2020, 2021
SCOPE	**Purpose of the QST cycle**	Check robustness of dominant justification narratives		Critical reflection on uncertainties and alternatives	
	Governance level	European	European	European	Local/Regional
	Geographical scale	National/ European	National/ River Basin/ European (Regionalized)	European	Local/ Regional
METHODS	**Narrative analysis**	Policy text analysis; scientific literature review	Policy text analysis, interviews (5)	Policy text analysis	Semi-structured interviews (27) to actors holding knowledge on water, food and energy management
	Quantitative analysis	Analysis of production, imports, and exports of biofuels in the Netherlands and Europe	GIS scenario of water-energy nexus for demographic patterns of	Analysis of nexus dimensions of electric vehicles: energy consumption, GHG	Multi-level diagnosis of water-food supply nexus patterns of farming systems. Energy cost

			extraction wells	emissions, local air emissions, labor investments and material requirements.	of water sources.
	Numbers-narratives relation	Negative feedback, falsification		Negative and positive feedback, explore uncertainties	
ENGAGEMENT	**Purpose**	Validation (or not) of the falsification of dominant narratives		Reflexivity on the narratives, co-creation of new narratives	
	Number and type of activity	1 workshop	Interviews Failed workshop	2 workshops	Interviews 2 workshops in the Canary Islands
	Engaged actors	Energy modelers and EU policymakers	EU policymaker, industry, academics, and relevant NGOs.	Regional cooperatives and civil society groups, urban planners and decision-makers at EU Regions & Cities week, PhD students	Agricultural and water management organizations, public authorities, academics, civil society, students

4 Discussion

Innovations are not just material objects. They are grounded in imaginaries that rely on values, emotions, and expectations beyond what can be discussed solely through quantitative assessments. A relational nexus lens can open the assessment of innovations to include the narratives and imaginaries that these innovations are grounded in, and which they contribute to, relating them to material dimensions. Our QST processes highlighted the dominant narratives justifying the implementation of nexus innovations in European

policies. In the biofuel and shale gas cases, we observed expectations for an energy-secure Europe grounded in political needs to overcome the bottleneck created by the dependence on imported oil and gas. To avoid a political stall, governance shifts to the management of expectations (Borup et al. 2006). On the other hand, the promotion of electric vehicles and alternative water resources relies on expectations of these technologies as effective solutions to pressing social-ecological concerns such as climate change and water scarcity. Ultimately, the four innovations provide an avenue for reconciling the tensions between conflicting policy goals (Kovacic, Rommetveit, and Strand 2020): with economic growth being continuously coupled with environmental protection, the EU may pursue its leadership for sustainable growth while depoliticizing the material requirements and impacts of such growth (Levidow 2013). Dominant narratives placed the innovations within nexus imaginaries (Cairns and Krzywoszynska 2016). By framing each solution as the most desirable one in relation to multiple and sometimes changing concerns, uncertainties associated with the innovations are minimized or ignored, tradeoffs are purportedly resolved, and possible alternatives are cast aside.

Our quantitative assessments served to explore whether the innovations' dominant narratives were coherent when checked from a multi-scale nexus perspective. For biofuels and shale gas, justifications were questioned with biophysical evidence, in order to falsify them; for electric vehicles and alternative water resources, the dominance of the normative-justification relationship was questioned, opening the space for alternatives to emerge. Looking back at Section 2, we asked whether the innovations meet their material expectations. For biofuels, this is clearly not the case. For shale gas, material expectations unfold across different scales. Individual wells provide a surplus of energy and economic revenue that for some landowners may justify the impacts over water and land. However, when it comes to the EU's expectations of using shale gas to transition to clean energy, this would not be possible at the large scale due to water and land requirements. For EVs, the answer is also "it depends": our case study highlighted the various sources of uncertainty tied to those expectations (for example, studies claiming that GHG emissions will be reduced with EVs, and studies claiming the opposite). For alternative water resources, material expectations are mostly met: these resources sustain a variety of farming systems and water tables have stopped dropping. In addition, there is a strong

sense of security derived from the lack of freshwater resources (controlled in a speculative private market). Farmers now know where they can get water, at stable supply and prices.

We also asked what uncertainties surround the implementation of these innovations. On one hand, ambiguity of goals allows for policy measures such as biofuels and shale gas to persist despite contrasting biophysical evidence. On the other, strict uncertainty and indeterminacy allow for electric vehicles and alternative water resources to be framed in a positive light, with ambiguity also playing a part in the justifications associated with these innovations. This view of uncertainties and their underlying politics casts doubt on whether multi-scale assessments can directly shift dominant policy narratives and imaginaries (Turnhout et al. 2020).

From an implementation perspective, our quantitative assessments were not discussed with EU policymakers, partially because of a strong resistance of actors from European institutions to get involved in the project. This led to the engagement of other actors who did not feel fully reflected in the narratives presented, while also having a limited capacity to directly influence European policies. The importance of engaging relevant actors from the onset of co-production processes has been extensively signaled (Norström et al. 2020). Yet, we have learnt that when those actors reject participating, QST may still offer relevant avenues for exploration.

A discussion built on both narratives and numbers offered the opportunity to collectively reflect on the ecosystem of narratives that surrounds complex sustainability challenges with a variety of actors. For example, in the electric vehicle workshops, existing evidence on how GHG emissions are tied to the size of vehicles sparked debates about the tension between environmental benefits of the vehicles, and the EU's priority of boosting its automotive industry. In the biofuel workshop, when presented with EU biofuel justification narratives and contrasting evidence, energy modelers acknowledged existing trade-offs in the biofuel supply chain, suggesting that biofuels tend to play a small part in the construction of their scenarios. In this sense, the modelers were already aware of the biophysical limitations played by biofuels. Grounding the discussion in both narratives and metrics created the opportunity to discuss how their own views of the role of biofuels differ from the EU's official framing. This outcome questions

the preference for using solely quantitative tools in the nexus literature (Albrecht, Crootof, and Scott 2018) by suggesting that qualitative and plural framings of nexus relations are crucial to bring politics into reflexive assessments (van Gevelt 2020).

In addition to discussing dominant narratives and their evidence base, for the cases of electric vehicles and alternative water resources the engagement processes served to open conversations on context and alternatives. The workshops on electric vehicles held space for imagining alternative solutions to the unsustainability of the transport system, by envisioning the future of cities and of rural-urban divides. The discussion focused on the potential roles of car-sharing, public transport, walking and cycling in shaping future transport systems. This, in turn, led to broader conversations about where responsibility lies, and about the local dimensions of mobility, suggesting that electric vehicles may be useful in some contexts, and less so in others. The workshops on alternative water resources focused on discussing what new roles could be envisioned for these innovations within futures with more sustainable farming practices. Framing the conversation around desirable futures helped expand the debate from the technicalities of water management to the difficulties small farming systems face to stay afloat within an export-imports based European food policy. Our outcomes in terms of contextualizing and broadening discussions, as well as empirical and methodological insights to STS, add to calls for “opening up” the assessment of innovations and of the nexus (Stirling 2008; Urbinatti et al. 2020).

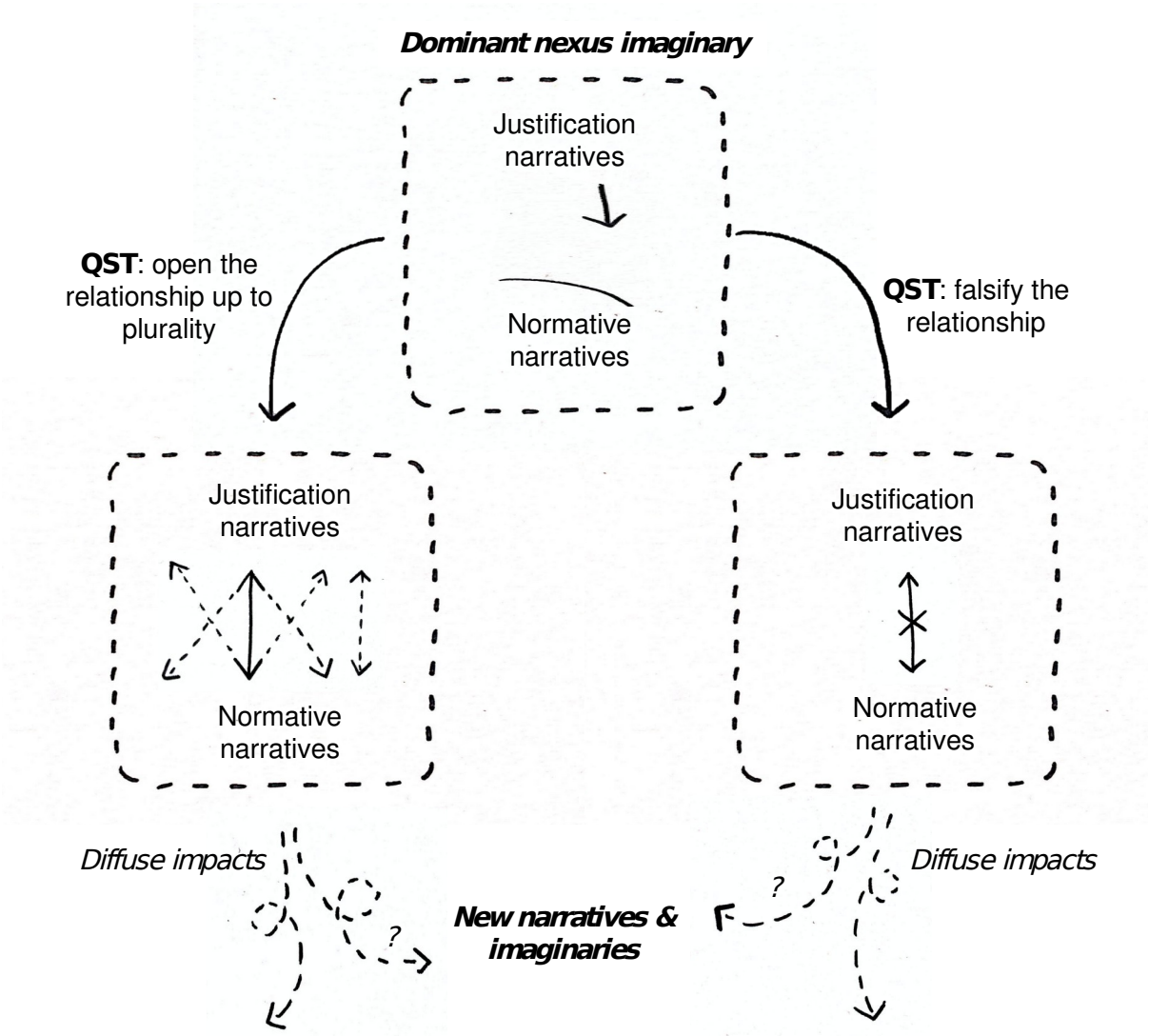

Figure 2. QST as a means to question dominant imaginaries

Building on our shared experiences, QST can be re-framed from the closed cycle of Figure 1 to a means of opening the debate of science-policy relations to wider audiences, discussing dominant imaginaries as shown in Figure 2. When the promotion of an innovation responds to vested interests, like we observed in the cases on biofuels and shale gas, the QST route of falsification can question whether dominant narratives are coherent by amplifying critical evidence and alternative narratives. This is a strategy to include "unknown knowns" in the for our four case studies, dominant EU narratives tie together economic growth, security, environmental protection, and local development. Nexus innovations are seen as a way to simultaneously address these multiple concerns, confirming

the existence of what has been termed in the literature as “nexus imaginaries” (Cairns and Krzywoszynska 2016).

In this context, simply presenting policymakers with biophysical evidence is not enough to generate change in their narratives. On one hand, innovations are inevitably tied to different types of uncertainty that may serve political purposes and cannot be reduced by producing additional quantitative assessments. On the other hand, there may be limited interest for these kinds of critical results, as our attempts to engage with policymakers suggest. This, however, does not mean that analyses such as QST, where relationships between numbers and narratives are outlined, do not have a place in the current ecosystem of science for policy. What we saw through our engagement events is that QST may be used to question existing narratives and co-create new imaginaries. In this way, by discussing innovations beyond their material dimensions, the nexus can become a lens that accommodates plural visions.

Given the experimental nature of the case studies, there are many limitations to QST in its current form, and to the meta-analysis that can be extracted from the four innovations. While we provided two main “routes” which may be taken through QST (falsification vs. opening up to plurality), the operationalization of QST at the methodological level is not yet formalized – in this first iteration, different researchers made different decisions regarding their own case studies. We hope that this paper can serve as a point of reflection for researchers to move forward in more coordinated steps. This includes engagement activities, an important part of QST that was implemented in different ways. Further discussion is needed to reflect upon the role of engagement in QST and more broadly in the analysis of science-policy relations. On this, the difficulty in engaging relevant actors from the onset was particularly limiting, and future iterations of QST may have to re-focus objectives by keeping this limitation in mind. When it comes to impacts, we mentioned in our discussion how QST may lead to diffuse impacts, which are harder to quantify. While we do not believe that these impacts should be reduced to metrics, it would be fruitful to think of ways to track these processes over time, for example through the analysis of the evolution of narratives, or the engagement of the same actors across the years. This would require multiple iterations of QST, while what we presented here was an individual “cycle.” We are aware that this kind of

work would require extensive time and energy, and that funding bodies may be reluctant to invest in tracking long-term, diffuse impacts of experimental work of this sort. Still, we hope that our reflections may provide food for thought for those researching nexus innovations and their role in science-policy relations, and that the insights generated by our first iteration of QST can enrich existing methods and approaches. process (Giampietro and Funtowicz 2020). Alternatively, when opportunities for pluralistic processes arise, one might opt for a co-creation route attending to different uncertainties in symmetrical dialogical relations (Giatti 2019). Rather than direct policy or narrative change, the outcomes from these processes might be diverse and diffuse. They extend beyond the observed timeframe and are harder to trace or quantify. In the long run, routes of this kind may contribute to shared alternative imaginaries that may, in turn, lead to changes in the governance of nexus innovations. Importantly, Figure 2 emerged from a first run of experimentation of QST: as such, steps are not yet formalized. While we believe that a degree of openness in the methodology is necessary to accommodate a variety of case studies, actors, and objectives, further testing and implementation are needed to discuss how QST can be used in consistent ways across diverse case studies.

5 Concluding remarks

Scientists are increasingly asked to produce policy-relevant research, intended as research that can have direct, quantifiable impacts on decision-making processes. In this paper, we have presented and reflected upon our experiences of implementing QST, an approach initially aimed at assessing dominant innovation narratives and empirically testing them through multi-scale nexus assessments, to replace them with narratives that are grounded in biophysical reality. Our experiences speak to the role played by socio-technical imaginaries in shaping policy solutions, particularly innovations. We found that for our four case studies, dominant EU narratives tie together economic growth, security, environmental protection, and local development. Nexus innovations are seen as a way to simultaneously address these multiple concerns, confirming the existence of what has been termed in the literature as “nexus imaginaries” (Cairns and Krzywoszynska 2016).

In this context, simply presenting policymakers with biophysical evidence is not enough to generate change in their narratives. On one hand, innovations are inevitably tied to different types of uncertainty that may serve political purposes and cannot be reduced by producing additional quantitative assessments. On the other hand, there may be limited interest for these kinds of critical results, as our attempts to engage with policymakers suggest. This, however, does not mean that analyses such as QST, where relationships between numbers and narratives are outlined, do not have a place in the current ecosystem of science for policy. What we saw through our engagement events is that QST may be used to question existing narratives and co-create new imaginaries. In this way, by discussing innovations beyond their material dimensions, the nexus can become a lens that accommodates plural visions.

Given the experimental nature of the case studies, there are many limitations to QST in its current form, and to the meta-analysis that can be extracted from the four innovations. While we provided two main “routes” which may be taken through QST (falsification vs. opening up to plurality), the operationalization of QST at the methodological level is not yet formalized – in this first iteration, different researchers made different decisions regarding their own case studies. We hope that this paper can serve as a point of reflection for researchers to move forward in more coordinated steps. This includes engagement activities, an important part of QST that was implemented in different ways. Further discussion is needed to reflect upon the role of engagement in QST and more broadly in the analysis of science-policy relations. On this, the difficulty in engaging relevant actors from the onset was particularly limiting, and future iterations of QST may have to re-focus objectives by keeping this limitation in mind. When it comes to impacts, we mentioned in our discussion how QST may lead to diffuse impacts, which are harder to quantify. While we do not believe that these impacts should be reduced to metrics, it would be fruitful to think of ways to track these processes over time, for example through the analysis of the evolution of narratives, or the engagement of the same actors across the years. This would require multiple iterations of QST, while what we presented here was an individual “cycle.” We are aware that this kind of work would require extensive time and energy, and that funding bodies may be reluctant to invest in tracking long-term, diffuse impacts of experimental work of this sort. Still, we hope that our reflections may provide food for thought for

those researching nexus innovations and their role in science-policy relations, and that the insights generated by our first iteration of QST can enrich existing methods and approaches.

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