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TESIS

The Water-Energy-Food Nexus: Trends, Trade-offs and Implications for Strategic Energies

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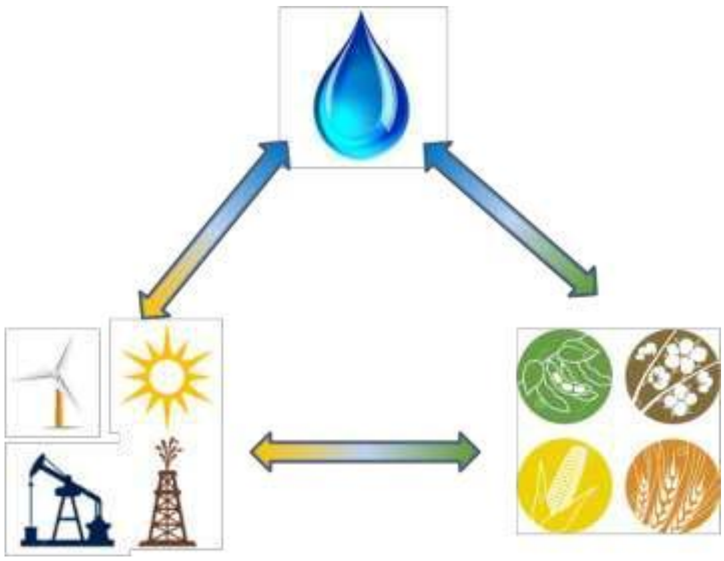
El nexo Agua-Energía-Alimentación: tendencias, intercambios e implicaciones para energías estratégicas



Memoria presentada para optar al grado de doctora por:

Beatriz Mayor Rodríguez

Bajo la dirección de los doctores:

Elena López-Gunn - Fermín Villarroya - Esperanza Montero

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List of acronyms and abreviations

ADB: Asian Development Bank

AEA: Agua-energía-alimentación

APPA: Asociación de Productores de Energías Renovables

BRIICS: Brazil, Russia, India, Indonesia, China and South

Africa CAP: Common Agricultural Policy

CDP: Carbon Disclosure Project

CCS: Carbon Capture and Storage

CEC: Contaminants of Emerging Concern

CEDEX: Centro de Estudios y Experimentación de Obras

Pública CHD: Confederación Hidrográfica del Duero

CLEW: Climate, Land, Energy and Water coalition

CO_2: carbon dioxide

CSCIM: Consejo Superior de Colegio de Ingenieros de

Minas CUAS: Comunidades de Usuarios de Aguas

Subterráneas DGA: Dirección General del Agua

DRR: Disaster Risk Reduction

EC: European Commission

EDR: European Development Report

EIA: Environmental Impact Assessment

EPA: Environmental Protection Agency

EPRS: European Parliament Research Service

ESCWA: United Nations Economic and Social Commission for Western Asia

ETSAP: Energy Technology Systems Analysis Program

EU: European Union

EWEA: European Wind Energy Association

FE2W: Food Energy Environment and Water

Network FAO: Food and Agriculture Organization

FH: Fractura hidráulica

GDP: Gross Domestic Product

GHG: Green House Gases

GIS: Geographic Information Systems

GMO: Genetically Modified Organism

GWOPA: Global Water Operators' Partnerships Alliance

GWP: Global Water Partnership

GWPC: Ground Water Protection

Council GWSP: Global Water System

Project HF: Hydraulic fracturing

IAEA: International Atomic Energy Agency

ICIMOD: International Centre for Integrated Mountain

Development ICT: Intelligent Communication Technologies

IDAE: Instituto para la Diversificación y Ahorro de la

Energía IEA: International Energy Agency

IGME: Instituto Geológico Minero Español

IHA: International Hydrogeologists Association

IIASA: International Institute for Applied Systems Analysis

IISD: International Institute for Sustainable Development

ISO: International Organization for Standardization

IPCC: Intergovernmental Panel on Climate Change

IRENA: International Renewable Energy Agency

IWRM: Integrated Water Resource Management

IWMI: International Water Management Institute

Junta CyL: Junta de Castilla y León

KTH: Stockholm`s Royal Institute for Technology

KTN: Environmental Knowledge Transfer Networks

LHP: Large scale Hydropower

MARM: Ministerio de Medio Ambiente Rural y Marino

MAGRAMA: Ministerio de Agricultura y Medio Ambiente

MCM: million cubic meters

MDG: Millennium Development Goals

MINETUR: Ministerio de Industria, Energía y Turismo

NAACP: National Association for the Advancement of Colored

People NETL: National Energy Technology Laboratory

NREAP: National Renewable Energy Action Plan

OECD: Organization for Economic Development and Cooperation

PV: Photovoltaic energy

RBO: River Basin Organism

RHP: Reservoir Hydropower

RoR: Run off river

RRC: Texas Railroad Commission

RU: Relative Units

SCADA: Supervisory Control and Data Acquisition

SDG: Sustainable Development Goals

SEI: Stockholm Environmental Institute

SIC: Sites of Community Interest

SHP: Small scale Hydropower

TCEQ: Texas Commission on Environmental Quality

TU: Total Units

TWDB: Texas Water Development Board

UCM: Universidad Complutense de Madrid

UCS: Union of Concerned Scientists

UN: United Nations

UNCED: Nations Conference on Environment and Development

UNDESA: United Nations Department of Economic and Social

Affairs UNIDO: United Nations Industrial Development Organization

UNECE: United Nations Economic Commission for Europe

UNEP: United Nations Environmental Program

UNESCO: United Nations Educational, Scientific and Cultural Organization

UNFCCC: United Nations Framework Convention on Climate Change

UNSGAB: United Nations General Secretary's Advisory Board

UNU: United Nations University

UNW-DPAC: UN-Water Decade Programme on Advocacy and

Communication USAID: US Aid

US: United States

US DOE: United States Department of

Energy US EIA: US Energy Information

Agency W4EF: Water for Energy and Food

WASH: Water, Sanitation and Hygiene

WBCSD: World Business Council for Sustainable

Development WC: Water consumption

WEC: World Energy Council

WEF: World Economic Forum

WEF Nexus: Water-Energy-Food Nexus

WERF: Water Environment Research Foundation

WEO: World Energy Outlook

WFD: Water Framework Directive

WHO: World Health Organization

WW: Water withdrawal

WWAP: World Water Assessment Programme

WWF: World Wildlife Fund

WWTP: Waste Water Treatment Plant

List of Units

Billion: 10^9

c€: eurocents

€/EUR: euro

GWh: Gigawatt hour (10^9 watts

hour) ha: hectare (10^4 square metres)

hm^3: cubic hectometres kg:

kilogram (10^3 grams) km:

kilometre (10^3 metres)

km^2: square kilometre (10^6 square

metres) kW: kilowatt (10^3 watts)

m: metres

Mm^3: million of cubic metres (10^6 cubic

metres) MW: Megawatt (10^6 watts)

MWh: Megawatt hour (10^6 watts

hour) %: Percentage

Tons: 10^6 grams

USD: US dollars

Glossary of terms

***Blue water*:** water contained in rivers, lakes, aquifers and wetlands (Molden, 2007). Withdrawn blue water can be given a consumptive or non-consumptive use depending on whether it is returned to the environment or made available for further use in the same geographical system (Hoekstra et al., 2011).

Consumptive use of water: consumptive use of water is defined as 'water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment' (Vickers, 2001).

Driver: a driver is a factor that directly influences or causes change (UK Misitry of Defense, 2014; FTP-GFAR, 2014).

Green water: water from rain and stored as soil moisture (Molden, 2007).

Natural capital: natural capital is defined as the stock of natural ecosystems that yields a flow of valuable ecosystem goods or services into the future (Costanza, 2008).

Outlook: A description of a future state or development that is considered likely (or at least plausible) given clearly defined logic and assumptions (FTP-GFAR, 2014).

Time Horizon: The farthest point in the futurethat one will consider in a Futures Study (FTP-GFAR, 2014).

Trade-off: the exchange of one thing or value in return for another, usually the loss of one benefit and the gain of another benefit. Trade-offs involve weighing many different factors in the decision making process, and include issues of equity, costs of the trade-off, the time required to realize benefits and losses, and a sense of wether or not the trade-offs will meet or assit management goals (Dunster, 1996).

Trend: general tendency or direction of a movement/change over time (FTP-GFAR, 2014). A discernable pattern of change (UK Ministry of Defense, 2014).

Reservoir hydropower plant: plants associated to artificial reservoirs created by building a dam to control the natural river flow (IEA, 2012a).

Resilience: resilience is the capacity of a system to absorb changes and tensions without collapsing and losing its functionality (Holling and Gunderson, 2002).

Run-of-River hydropower plant: plant harnesses energy for electricity production mainly from the available flow of the river (IEA, 2012a).

Uncertainty: a state of having limited knowledge about the future (FTP-GFAR, 2014).

Water consumption (WC): water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment (Vickers, 2001). Water evaporated, either by evapotranspiration or by direct evaporation, is here considered as non-available for further use within the basin system, provided that this water can physically migrate to other regions when entering the global atmospheric cycle. The same applies to water diverted into the sea.

Water withdrawal (WW): water diverted or withdrawn from a surface water or groundwater source (Vickers, 2001; Hoekstra et al., 2011). According to this definition, WW makes reference to blue water abstraction, when water is physically diverted or taken from a water source, to be given either a consumptive or a non consumptive use.

Executive summary

Since the strong interdependencies between water, energy and later food were first identified, this topic has been gaining importance at the international level and for the business sector. Over the last five years, the need to characterize and understand the complex network of interconnections and interdependencies within the so called Water-Energy-Food (WEF) nexus has been strongly emphasized. Some of the most important knowledge gaps in the field include the following: 1. Better understanding of the whole set of interconnections, trade-offs, crossed efficiencies and synergies between the WEF systems to better inform decision makers on technical choices and best strategies; 2. More concise and harmonized conceptual and analytical frameworks for the *Nexus Approach*, as well as formulas to deal with complexity and guide implementation; 3. More and better quality data, particularly on availability and use of surface and especially groundwater resources, impacts of hydropower on aquatic ecosystems, water use, consumption and impacts by the energy sector, among others; 4. Need for harmonized tools and methodologies for water and energy accounting; 5. Applied case studies to identify and account for trade-offs in the local contexts; 6. Policy and regulatory coordination; and 7. Social awareness and communication around the nexus (Rodríguez et al., 2013; Hoff, 2011).

Born on the eve of 2014, the *United Nations's International Year for Water & Energy*, this Phd research aims to contribute to fill some of these gaps by focusing on three research objectives: 1. Tracking down and clarification of nexus trends at a global scale; 2. Discussion on the WEF nexus concept and proposal of a methodology to conduct regional assessments; 3. Elaboration of applied case studies to analyse relevant WEF nexus related problems, particularly the accountability of WEF nexus trade-offs, the analysis of impacts and contributions from hydropower, and the analysis of potential implications for water security of hydraulic fracturing.

The first objective is addressed through an in depth study of the main drivers influencing the WEF nexus, together with the most important trends and current research lines. This analysis is complemented by a prospective exercise to explore the future evolution of selected variables with particularly high levels of uncertainty. It consists of a Delphi survey gathering the visions and contributions from Spanish experts on the topic. The results indicate the importance of technology innovation and transfer as the main conditioning factors to achieve energy and water security. In terms of energy, biofuels and shale gas are perceived as the energies with highest potential impacts on water quantity and especially on water quality.

The second objective is developed through the analysis of existing WEF nexus conceptualizations and frameworks. This is followed by the proposal of a methodology to identify and assess WEF trade-offs that can help orient coordinated and efficient resource management strategies. This methodology is applied to the Spanish Duero River Basin as a case study, resulting in the accounting of WEF nexus flows, the identification of policy integration and coordination gaps and related conflicts in the basin. The main conflicts are related to the rising electricity prices constraining modernized irrigation and wastewater treatment, as well as to water-energy crossed efficiencies (rebound effects) and social concerns on possible impacts on water from the potential hydraulic fracturing development.

The third objective includes the development of two case studies. A first case aims to put into perspective the consequences of a large hydropower vs small hydropower deployment at a basin scale. This is done by analyzing comparatively the cumulative contributions to regional water and energy security, as well as the associated cumulative impacts from both large and small hydropower in the Spanish section of the Duero basin. The results suggest that in overall terms large hydropòwer has higher contributions to energy and water security, with better performance in 10 of the 12 indicators developed and assessed. As regards to impacts, in absolute terms large scale hydropòwer generates higher cumulative impacts on flow regime and habitat loss, whereas small hydropower has higher cumulative impacts on river connectivity. In relative terms small hydropower has higher impacts per unit of energy produced in all impact categories, showing lower efficiency in terms of impact/energy performance ratio.

The second case study reflects on the debate over the possible expansion of the U.S. 'shale gas revolution' to the European and specifically the Spanish contexts and its potential environmental consequences. It consists of a comparative analysis of the legal, social and water contexts of hydraulic fracturing in two areas: the state of Texas in the U.S. - with an established hydraulic fracturing industry – and the case of Spain in a European context. The study shows important contextual differences in aspects related to the regulatory cultures and public reaction, the role of central government, regulation capacity and oversight, royalties and disclosure. These aspects reflect the extent to which water security can sometimes be a trade-off for energy security. The study highlights a set of key elements for managing the water risks from hydraulic fracturing: best available practices and technologies, baseline and periodic monitoring, Environmental Impact Assessment, regulatory costs, social participation and disclosure.

Overall, the main original scientific contributions from this thesis include: first, an identification and validation of key nexus drivers, trends and challenges based on the available knowledge in both the literature and expert knowledge; second, an analysis on the potential future evolution of key uncertain nexus variables based on expert knowledge; third, the proposal for a sequential and comprehensive methodology to perform WEF analyses and diagnoses at different scales; fourth new evidence based knowledge related to WEF trade-offs, impacts and contributions from hydropower at regional level in the Spanish Duero basin; fifth, recommendations based on the analysis of real case studies on critical aspects to be considered by governments when considering hydraulic fracturing, to safeguard regional water security. The thesis ends providing a set of conclusions and recommendations for future research on the WEF nexus. It highlights the critical importance of research and action on social, political and economic aspects, which may drive equal or even higher advancements than technological aspects to solve WEF challenges. It also warns on the potential water and food externalities from low carbon policies based on certain energy technologies, particularly first generation biofuels, hydraulic fracturing, carbon capture and storage and wide hydropower deployments. Additionally, it identifies low water footprint renewables, wastewater treatment and water reuse, coupled technological solutions and decentralized approaches as specially promising opportunities where further research, investment and political support is required. With regards to the Spanish case, the main conclusions and policy recommendations put an emphasis on the following points. First, the critical importance to support the expansion of renewables and self energy production to advance towards energy sustainability. Second, the outstanding opportunities to expand the hydraulic pumping and storage potential to enhance energy independence. A third point highlights the importance of evaluating the energy footprint from irrigation and its consideration within water and agriculture plans. Finally, the need to carefully assess the feasibility of hydraulic fracturing projects, paying special attention to five aspects: baseline/monitoring, regulatory costs, participation and Environmental Impact Assessments and disclosure.

Resumen ejecutivo

Desde la pionera identificación y reconocimiento de las interdependencias entre el agua, la energía y más adelante la alimentación, este tema ha venido ganando importancia a nivel internacional y empresarial. Durante el último lustro, la necesidad de expandir el conocimiento acerca del concepto e implicaciones del llamado Nexo Agua-Energía-Alimentación (AEA), definir los principios que fundamentan este enfoque e identificar sus principales retos y oportunidades se han ido fraguando en la comunidad científica, el sector privado, las organizaciones internacionales y la sociedad civil. Entre las brechas de conocimiento más reconocidas en este campo se encuentran las siguientes: 1. necesidad de una mejor comprensión del conjunto de interconexiones, intercambios, eficiencias cruzadas y sinergias entre los sistemas AEA, con el fin de informar a los gobernantes en la selección de las mejores técnicas y estrategias; 2. necesidad de un marco conceptual y analítico del Enfoque Nexo más conciso y armonizado, así como fórmulas para lidiar con la complejidad y guiar la implementación; 3. necesidad de mejorar la cantidad y calidad de datos e información, particularmente en lo referido a disponibilidad y uso de los recursos hídricos, impactos de los complejos hidroeléctricos sobre los ecosistemas acuáticos y uso, consumo e impactos de las tecnologías energéticas sobre los recursos hídricos, entre otros; 4. necesidad de herramientas y metodologías armonizadas para la contabilización de agua y energía; 5. necesidad de casos de estudio aplicados para identificar y contabilizar los intercambios en los contextos locales; 6. necesidad de coordinación política y regulatoria; 7. necesidad de concienciación social y comunicación (Rodriguez et al., 2013; Hoff, 2011).

Nacida a las puertas de 2014, el *Año Internacional de Naciones Unidas del Agua y la Energía*, esta tesis doctoral pretende unirse a los amplios esfuerzos por aportar algo de luz sobre este tema, mediante el desarrollo de tres objetivos: 1. seguimiento y clarificación de tendencias a escala global; 2. discusión del concepto del Nexo AEA y propuesta de una metodología para realizar análisis regionales; 3. elaboración de casos de estudio para analizar problemáticas relevantes relacionadas con el nexo, particularmente la contabilización de intercambios, el análisis de impactos y contribuciones de la hidroeléctrica, y el análisis de potenciales implicaciones de la fractura hidráulica para la seguridad hídrica.

El primer objetivo es desarrollado mediante un estudio en profundidad de las principales fuerzas que influyen en el nexo, junto con las tendencias y líneas de investigación más importantes en la actualidad. Este análisis es complementado con un ejercicio de prospectiva que explora la evolución futura de una selección de variables con gran nivel de incertidumbre. Dicho estudio consiste en una encuesta Delphi que recoge las visiones y contribuciones de expertos españoles en el tema. Los resultados resaltan la importancia de la innovación y transferencia tecnológicas como principales condicionantes para alcanzar la seguridad hídrica y energética. En términos de energía, los biocombustibles y el gas no convencional son percibidos como las energías con mayores potenciales impactos sobre la cantidad y calidad de los recursos hídricos.

El segundo objetivo se aborda mediante el análisis de las conceptualizaciones y marcos teóricos existentes sobre el Nexo AEA, y la posterior proposición de una metodología para la identificación y evaluación de los intercambios entre AEA que permita orientar el diseño de estrategias de gestión de recursos coordinadas y eficiente. Esta metodología es aplicada a la cuenca española del Duero como caso de estudio, resultando en una contabilización de los flujos e intercambios entre AEA y la identificación de deficiencias de coordinación e integración política, así como de los conflictos derivados. Se concluye que

muchos de estos conflictos están relacionados con los crecientes precios de la electricidad, con efectos negativos sobre los regadíos modernizados y el tratamiento de aguas. Otro conflictos relevantes son los derivados de eficiencias cruzadas en agua-energía (efectos rebote) y preocupación social acerca de los posibles impactos de un desarrollo de la industria de fractura hidráulica sobre los recursos hídricos.

El tercer objetivo incluye el desarrollo de dos casos de estudio. El primero pretende poner en perspectiva las consecuencias de una implantación masiva de proyectos hidroeléctricos a escala de cuenca, en respuesta al gran debate internacional acerca de la sostenibilidad tanto de la macro como de la mini hidráulica. Esto se realiza mediante el análisis comparativo de las contribuciones agregadas a la seguridad energética e hídrica del potencial hidroeléctrico de gran y pequeña escala en la cuenca del Duero, así como de los impactos agregados asociados. Los resultados sugieren que en términos generales la macro hidráulica contribuye en mayor medida a la seguridad hídrica y energética, con mejores resultados en diez de los doce indicadores estimados. En relación a los impactos, en términos absolutos la macro hidráulica genera mayores impactos agregados sobre el *régimen de flujo* y la *pérdida de hábitat*. En términos relativos, la mini hidráulica tiene mayores impactos por unidad de energía producida en todas las categorías, mostrando menores eficiencias en términos de ratio rendimiento energético/impacto.

El segundo caso de estudio reflexiona sobre el debate acerca de la posible expansión de la 'revolución del gas de esquisto' estadounidense a los contextos de Europa y España y sus posibles consecuencias ambientales. Éste consiste en un análisis comparativo de los contextos legal, social e hídrico de la fracturación hidráulica en dos casos: el estado de Tejas en Estados Unidos, con una industria de fracturación hidráulica madura y activa, y el caso de España con una actividad incipiente en un contexto europeo. El estudio muestra importantes diferencias contextuales en aspectos de cultura legislativa y reacción pública, el papel del gobierno central, la capacidad regulatoria y de supervisión, los derechos sobre la tierra y la publicidad de la información. Estos aspectos reflejan hasta qué punto la seguridad hídrica se encuentra a expensas de la seguridad energética. El estudio concluye resaltando una serie de aspectos críticos para gestionar los riesgos de la fractura hidráulica sobre los recursos hídricos: mejores prácticas y tecnologías disponibles, monitorización previa y continuada durante el proyecto, Evaluación de Impacto Ambiental, costes regulatorios, participación social y transparencia.

En resumen, las principales contribuciones originales la ciencia aportadas por esta tesis incluyen las siguientes: primero, una panorámica de las principales fuerzas, tendencias y retos del nexo basado en el más reciente conocimiento disponible en la literatura y nutrido por expertos internacionales; segundo, una panorámica de la evolución a futuro de variables clave en el nexo con gran nivel de incertidumbre, basada en conocimiento experto; tercero, la propuesta de una metodología integral y secuencial para realizar estudio y diagnósticos AEA a distintas escalas; cuarto, conocimiento inédito y probado sobre los intercambios AEA, así como de los impactos y contribuciones agregadas de la hidroeléctrica a nivel local en la cuenca del Duero; quinto, recomendaciones basadas en un análisis de casos reales sobre aspectos críticos a considerar por los gobiernos que apuesten por la fractura hidráulica, con el fin de salvaguardar la seguridad hídrica local. La tesis concluye con una serie de conclusiones y recomendaciones para el futuro de la investigación en el nexo. Resalta la importancia de investigar y actuar en aspectos sociales, políticos y económicos, los cuales pueden desencadenar avances equivalentes o incluso mayores que los tecnológicos para superar los retos del Nexo. También previene sobre las externalidades sobre el agua y la alimentación que podrían acarrear las políticas bajas en carbono basadas en ciertas tecnologías, particularmente los biocombustibles de primera generación, fracturación hidráulica, tecnologías de captura y almacenaje de carbono y desarrollos hidroeléctricos masivos. Asimismo, identifica las energías renovables de baja huella hídrica, el tratamiento y reutilización de agua, los acoplamientos y combinaciones tecnológicas y las soluciones descentralizadas como oportunidades prometedoras que merecen mayores esfuerzos de investigación, inversión y apoyo político. En relación al caso de España, las principales conclusiones y recomendaciones aportadas hacen hincapié, en primer lugar, en la crítica importancia de apoyar y promover la expansión de las renovables y la autogeneración energética para avanzar hacia la sostenibilidad energética. En segundo lugar, se resaltan las oportunidades que ofrece la expansión del bombeo y almacenamiento hidráulico para aumentar la independencia energética. En tercer lugar, se enfatiza la importancia de evaluar la huella energética del regadío y su consideración en la planificación hidrológica y de la agricultura. Finalmente, se reitera la necesidad de evaluar cuidadosamente la factibilidad de los proyectos de fracturación hidráulica, poniendo especial atención en aspectos de monitorización, costes regulatorios, participación, evaluación de impacto ambiental y transparencia.

CHAPTER 1

RESEARCH CONTEXT AND THESIS STRUCTURE

Chapter 1. Research context and thesis structure

1.1. Introduction to the research context

1.1.1. Water-energy-food nexus: the global challenges

Water, energy and food are intrinsically interrelated. Energy is needed to pump, purify and distribute fresh water, as well as for the collection, conveyance and treatment of wastewater. Energy requires water for cooling power plants, as a source for energy production in hydropower and ocean energy, and to grow crops or cellulosic materials for biofuels. Water and energy are required for food production to grow crops, feed cattle and run farms, elaborate processed foods and run the supply chain from production to distribution. And food has been used as an input material to produce biofuels for transport and energy production. There is thus a complex network of interrelations and interdependences between these three elements, which constitute vital resources for human beings historically underpinning the establishment and consolidation of human settlements. An example is the settlement of ancient human societies next to rivers and vegetated areas to get water, food and biomass to produce the first type of energy ever known: fire.

The realization of the water-energy-food interconnections – what has been called the water-energy food nexus (WEF nexus) – has always been present throughout human history to a certain extent, and civilizations and societies have taken advantage of its emerging opportunities to promote human development, progress and economic growth. However, this same human development has boomed since the industrial revolution and especially during the last 70 years, with natural resources exploitation trends exceeding environmental capacities. This has driven a change in global resource dynamics and fluxes, to the point of approaching or even surpassing planetary boundaries (Erb et al., 2012). The disruption of this natural equilibrium is causing emerging conflicts and crossed effects derived from WEF nexus interdependences – for instance energy breakdowns due to insufficient availability of water for cooling (i.e. France 2003), local food security conflicts due to competition between crop production for food and energy (i.e. soy production in China), or groundwater overexploitation due to irrigation water pumping (i.e. India or Spain)-, raising national and international concern and recognition on the importance of understanding and properly managing the WEF nexus to help prevent future water, energy and food crises at local, regional or even global scales.

Population growth rates have surged in the last 60 years, doubling from 2.5 billion to 5 billion between 1950 and 1990 and up to 7 billion in 2010. This growth is expected to continue to reach around 9 billions by 2050 (UN, 2014), causing food demand to double by 2050 (Tilman et al., 2011). Food production it is expected will need to be increased by 60% to meet this growing demand (FAO, 2012), requiring important improvements in agricultural productivity to avoid an increase in cultivated land above 70 million ha (Alexandratos & Bruinsma, 2012). In this context, important conflicts could be expected, especially in regions like areas in Latin America, South East Asia and in Africa where hunger and poverty problems are particularly acute. Meanwhile, urbanization will continue to expand, with urban areas expected to shift from the present 49% of the world population to 70% by 2050 (FAO, 2012). As a result global food demands will be more spatially concentrated, giving increasing importance to global food trade and markets and generating considerably higher transportation requirements and externalities.

Water demands have also increased considerably during the last century. According to the Organization for Economic Cooperation and Development (OECD) scenarios (2012), global water demands are expected to increase by 55% from 2012 to 2050, with the highest increase registered by the manufacturing sector (+400%), followed by energy (+140%) and domestic (+130%) sectors, leaving little room for agriculture, currently the biggest user, which could reduce its demands by 5% through the application of water efficiency measures (OECD, 2012). However, water demand across sectors varies strongly across countries depending on their economic activities. For example, in the United States 40% of overall national water withdrawals are caused by thermal power energy production (UCS, 2010). In contrast, in Mediterranean countries between 65% and 85% of water withdrawals are from the agricultural sector, mainly for irrigation (Wriedt et al., 2008). Overall, the rise in water demand will be especially acute in emerging countries like India and China, and will pose important threats to water availability in arid and semi-arid areas like the Middle East, South Asia, the South West of the United States (U.S.) and Central America, certain parts of Australia and the Mediterranean region. Water scarcity is an increasing trend affecting a growing portion of the planet, where the number of regions experimenting constraints to balance water supply and demand is on the rise. The United Nations estimate that by 2050 almost half of the world population will be living in water stressed areas (WWAP, 2012).

Water scarcity and the increased pressure on water resources (see Figure 1.1) are also seriously impacting natural ecosystems (UNEP, 2009). Natural ecosystems require water in certain quantities and qualities to optimally maintain their full functionality and provide the array of services and functions that make planetary and human life possible (WWAP, 2012). Ecosystems are at the heart of the water cycle - and of the nexus -, and recognizing their role in providing a variety of services is essential since awareness on ecosystems affected by resource mismanagements is critical to ensure that short-term gains (such as energy generation) do not undermine future resilience and long-term environmental sustainability (UNEP, 2015).

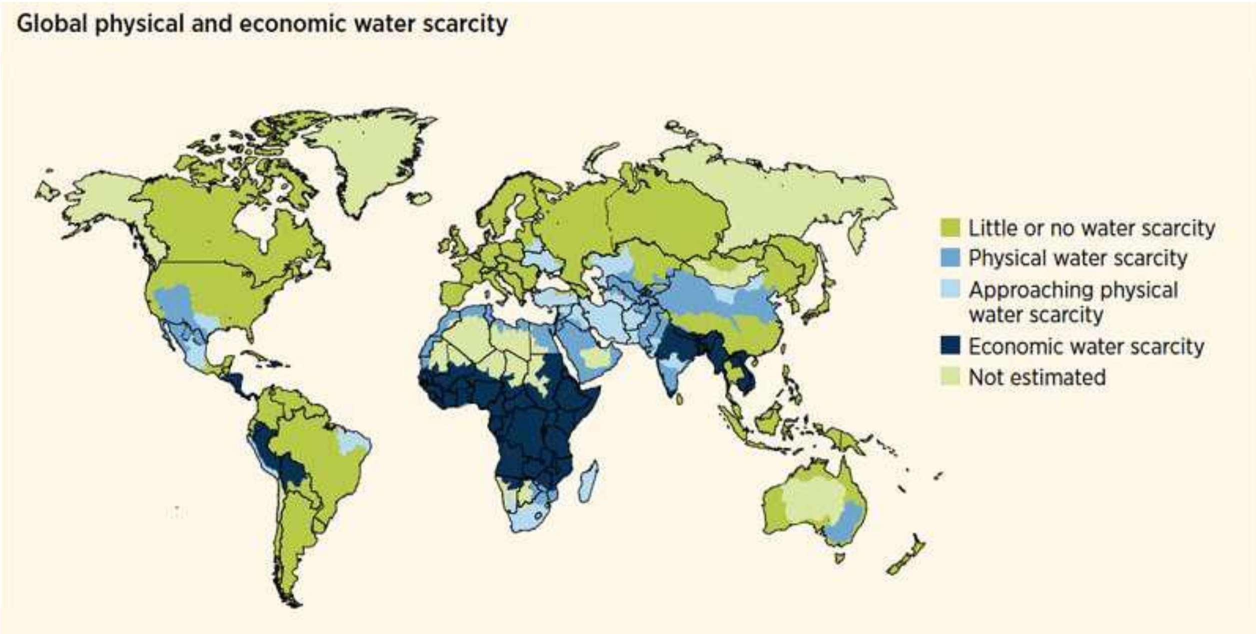

Fig. 1.1. Global physical and economic water scarcity. Source: WWAP, 2012.

Energy demands have doubled in the last four decades and are expected to rise 37% by 2040, with most of this increase taking place in non-OECD countries (IEA, 2014). Fossil fuels currently take 82% share in the primary energy mix and their role is not expected to change considerably in the future, with an estimated downfall to 75% by 2040 (IEA, 2014)[1]. The share of biofuels use in total transport may rise from 2% to 6% between 2010 and 2035, while renewable energies may reach 31% in the global primary energy mix by 2035 under a New Policies scenario (WEO, 2012). Energy production increases in the United States and Latin America will mainly come from non-conventional fossil fuels, whereas Asia will continue to rely strongly on coal and further expansion of their biofuel production, with considerable water quantity and quality externalities (WWAP, 2014). Meanwhile Sub-Saharan Africa, which has the greatest untapped hydropower potential in the world, may go for this option if regional governments find ways to tackle the great associated financial challenge (WWAP, 2014). On this basis, the evolution of water demands for energy, is an important factor conditioning future energy security, and in turn water demand will depend to a great extent, on the technological choices made, as well as on the application of water conservation and efficiency measures and technologies such as efficient cooling systems (Rodríguez et al., 2013).

Another key factor putting additional pressure to the projected imbalance in natural resources dynamics is climate change. Climate change is both affecting and affected by the WEF nexus, with multiple bidirectional interactions that intertwine within the network of water-energy-food interconnections. Climate change has been mainly driven by anthropogenic greenhouse gases (GHG) emissions to the atmosphere since the industrial revolution, and especially over the last 50 years (Bates et al., 2008). A high percentage of these emissions come from the burning of fossil fuels for transport and energy production (i.e. CO_2 emissions from thermal power, water vapour from cooling towers in thermal and nuclear power), together with industrial activity. A portion of GHG also come from crop fields dedicated to food and biofuel production, compounded by the massive cut down of both temperate forests and tropical forests (natural carbon sinks) to expand agricultural areas contributing to speed up global warming (Bates et al., 2008). In addition, climate change is driving a whole series of phenomena that have negative impacts on future water, energy and food security that can exacerbate nexus conflicts. For instance, an increase on the frequency and magnitude of extreme climatic events like prolonged droughts, floods, heat waves or tornados will pose important threats to water and energy infrastructure, water availability for food and energy production and potential crop failures, among others. Increasing rainfall variability and reduced average rainfall in many areas will constrain current and future hydropower production, impact on rain fed agriculture while increasing competition for water among sectors (WWAP, 2014). Meanwhile, climate change is also indirectly conditioning energy technology choices through the onset of climate change mitigation policies and global agreements which call for the adoption of so called ‘low or lower carbon technologies’ that in some cases have important water trade-offs, such as biofuels, shale gas or carbon capture and storage technologies (CCS).

After this panoramic it can be appreciated that increasing water, energy and food demands may threaten resource security and exacerbate competition and conflicts in the future, thus bringing social instability to many regions. In this context, there is increasing international recognition on the need to take action to revert these trends and shift towards the sustainable and coordinated management of water, energy and food resources - that is the adoption of a 'nexus' approach - to achieve society´s transition towards a green economy and hence wider global sustainability (Hoff, 2011). However, this is not an easy task, but

[1] The COP21 negotiations and resulting agreements in Paris however could change these projections.

requires a great shift in political will and attitudes that goes from recognition to understanding, adoption and implementation. It requires leaving behind the traditional silos approach and adopting a holistic, bottom-up, multisectorial, communicative and cooperative approach between sectoral institutions and policies, that permeates to the rest of stakeholders to ensure the coordinated, dynamic and adaptive governance of natural resources. Thus the nexus challenge extends beyond the institutional and policy levels, and so do its limitations. The 'nexus approach' paradigm, though based on a reality that has always been there, has gained urgency due to the simultaneous increase in demand on resources, driven by population growth and development yet there is still certain vagueness in its formulation and definition as a framework for action (ESCWA, 2015). Meanwhile, the existence of important knowledge gaps and uncertainties related to the understanding of the nexus and its implication has been internationally recognized. That is a call for further study and research on these issues that can help to reduce uncertainty and support informed political decision making (UNEP, 2015). Some of the main nexus challenges and uncertainties generally identified include the following:

- **Better understanding.** Further identification and understanding on the whole set of interconnections, trade-offs, crossed efficiencies and synergies between the water, energy and food systems to better inform decision makers on technical choices and best strategies (Rodríguez et al., 2013; Hoff, 2011).
- **Better defined and concise approach.** A harmonized 'nexus database' or analytical framework that could be used for monitoring or for trade-off analyses, as well as formulas to deal with complexity and to help guide implementation (Hoff, 2011; WEF, 2011; Bizikova et al., 2013).
- **Data scarcity.** There is a need for more and better data and monitoring of availability and use of water resources, particularly regarding groundwater; more knowledge on the impacts of hydropower and other water resources development on aquatic ecosystems; data on consumptive water use in the energy sector, compared to withdrawal data (WWAP, 2014; Rodríguez et al., 2013; Hoff, 2011).
- **Tools and methodologies.** Full life-cycle assessments in terms of water and energy are required; further research on energy productivity in agriculture; development of uniform resource accounting tools (e.g. harmonized water footprint) (Hoff, 2011).
- **Lack of accounting studies.** Most of the existing analyses are focusing on physical and technical variables. Few analysts are trying to quantify the trade-offs (Rodríguez et al., 2013).
- **Scale and time.** There is not clarity on which scale and time horizons are the most appropriate for dealing with nexus issues and for nexus effective management and planning (Rodríguez et al., 2013)
- **Policy and regulatory coordination.** Policy fragmentation and lack of integrated or at least coordinated regulatory frameworks and planning for the three sectors is an important challenge. Further regulation is needed of certain aspects like water quality standards (Rodríguez et al., 2013; Hoff, 2011).
- **Social awareness.** Lack of social awareness due to the lack of information and communication vehicles that connect civil society to the international and scientific discussions, challenges and concerns. This information - communication gap hinders wider emergence and adoption of responsible consumer responses.

1.1.2. The Water-Energy-Food nexus in Spain

Spain starts from its geographical position of limited resource availability together with European Union (EU) membership – which translates into the influence and compliance with European policies and targets. This means balancing national needs and interests with water and energy policies to face complex decisions including sometimes diverging regional, national and local roadmaps.

In terms of water, Spain has important annual rainfall and water availability differences between regions, which has generated not only upstream-downstream conflicts in the past but also inter-basin conflicts on water allocation. Meanwhile, the high intra-annual or seasonal rainfall variability in most basins, with a lower rainfall season coinciding with the peak demand period for irrigation and urban supply (i.e. for tourism), has historically involved a need for anticipatory water planning and management. This motivated the emergence in Spain of the first examples of river basin management in the world and in Europe (Omedas et al., 2011) and the implementation during the 20th century of the development of complex water infrastructure aimed at increasing urban and irrigation water supply security through the creation of over 1,000 dams and 11 inter-basin transfers (see Figure 1.2).

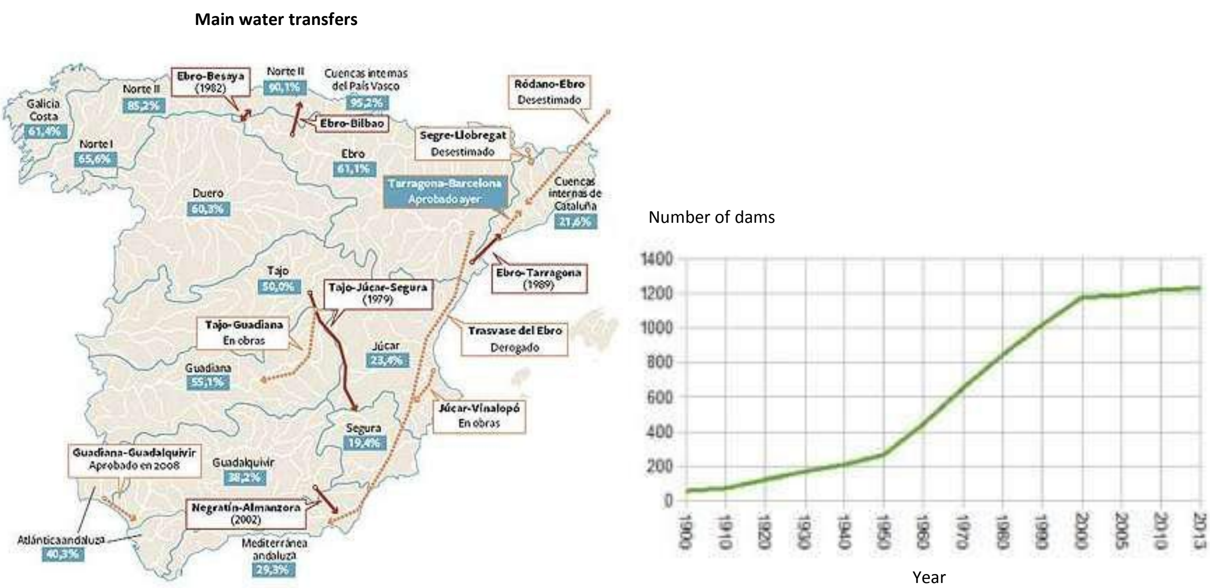

Fig. 1.2. Main water transfers and number of dams built during the 20th Century.

Source: MARM and SPANCOLD.

Over the last two decades Spanish water policy has been strongly influenced by EU water policy, especially since the endorsement of the EU Water Framework Directive. This Directive reinforced the Spanish model of water management using the river basin as the main management unit, and started a whole process of assessment and evaluation of the status of Spanish water bodies, revision of water plans, designing a series of measures to meet targets to restore degraded water bodies to meet normative requirements. In this evaluation most of Spanish water bodies have shown a high level of physical or ecological degradation due to urban and industrial discharges, diffuse pollution, high physical modifications due to existing water infrastructure and groundwater overexploitation. The general delay showed in the implementation of the Directive requirements by Spain in the first planning stages - a three year delay in the submission of the 2009-2015 water plan caused Spain to be taken to court and fined by the EU (European Commission, 2011). This contrasts with the considerable progress shown by some regions. For instance, the Segura river has shifted over the last ten years from being the most polluted river in the country to nowadays meeting the good water quality status requirements (UNW-DPAC, 2015a).

In terms of energy, Spain imports 70.5% of its internal energy consumption (Eurostat, 2015). 70% of its natural gas imports come from only three countries, Argelia (37.5%), Nigeria (18.3%) and Qatar (13.8%), whereas oil imports are more diversified (at least twelve countries with the highest percentage (15%) coming from Russia) (Rodríguez, 2012). The internal energy production mix is formed in order of importance by nuclear (43.8%), wind, solar and geothermal (22.7%), bioenergy and waste (17.8%), hydropower (9.4%), coal (5%), oil (1.1%) and gas (0.1%) as shown in Figure 1.3.

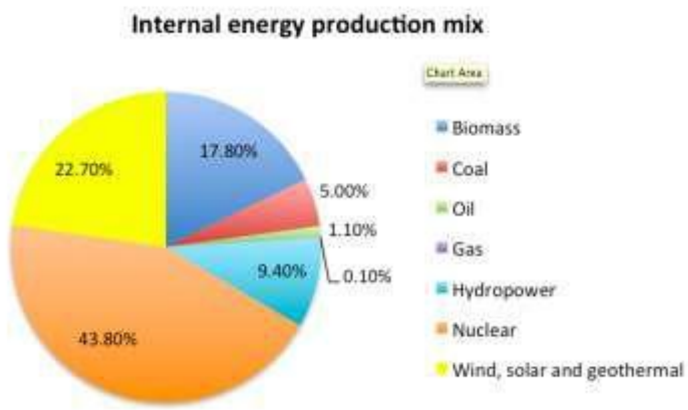

Fig. 1.3. Own elaboration from MINETUR (2013).

Nuclear and hydropower have historically constituted the core of Spanish internal energy production before renewables started to take off over the last two decades, pushed in part by the European renewable energy policies and targets and the feed-in tariffs and subsidies to enable market competitiveness. The greatest deployment was made in small scale hydropower and wind followed by solar power. However, during the recent economic crisis, the removal of subsidies and certain unfavourable policy measures (including a moratorium for renewables and energy self-generation) have caused a fall in the sector that risks future advances towards a higher share in renewable, even threatening not to meet European targets 2030 (APPA, 2015). When looking at water use for internal energy production, hydropower accounts for the highest annual water withdrawal (WW) and consumption (WC) rates with 24,400 Mm^3 and 1,200 Mm^3 respectively, followed by nuclear power (WW= 40,500 Mm^3, WC = 100 Mm^3), thermal coal (WW= 2,250 Mm^3, WC = 100 Mm^3), thermal natural gas (WW= 1,300 Mm^3, WC = 50 Mm^3), thermal oil (WW= 450 Mm^3, WC = 30 Mm^3), thermal biomass (WW= 100 Mm^3, WC = 10 Mm^3) and finally solar (thermal and photovoltaic (PV)), wind and geothermal (less than 20 Mm^3)(Hardy & Garrido, 2012). In fact hydropower together with irrigation constitute the main pieces for water use, standing as privileged users in the Spanish hydraulic paradigm (López-Gunn et al., 2012a). Recently, the discovery of shale gas formations in Spain has brought non-conventional shale gas onto the scene, attracting international oil and gas business interests, as well as the government, due to the potential for higher energy independence while at the same time it has raised social concern. However, this scenario entails a series of environmental risks that -as discussed later in this thesis - need to be considered.

In terms of food, agriculture is responsible for almost 70% of total water withdrawals in the nation whereas the contribution to national GDP has been decreasing from 11% in 1970 to around 3% since 2010 (Pampillón, 2014). However, agriculture has traditionally received considerable attention and recognition in the country, especially after a hard economic crisis at the end of the 19th century that placed water and irrigated agriculture as a symbol of prosperity and progress (López-Gunn et al., 2012a). It became a privileged water user, water rights were awarded without necessarily always confirming the existing available resources – which means that demand nowadays can only be met in years of high rainfall in many basins without putting pressure on existing resources. Furthermore, social and infrastructural structures were created for surface and groundwater irrigation. Two political factors have strongly influenced the evolution of agriculture over the last two decades. The first was the implementation of the EU´s Common Agricultural Policy, which involved the provision of subsidies for the production of certain crops to increase European internal self-supply and competitiveness of agricultural products (European Commission, 2012). This policy induced in Spain and most of European countries an important process of agricultural intensification and mechanization. Such processes combined with free trade within the Union and thus larger makets, gave both a competitive advantage to irrigated agriculture with a large pool of potential consumers i.e. for fruit and vegetables, leading to a shift towards higher value crops. This also translated in land use and crop changes, soil degradation and environmental pollution, while in some cases creating a dependence of agricultural rents on external subsidies (Salmoral, 2014). Although several CAP reforms have been approved to mitigate these effects throughout the last decade, the effects on the agricultural system and Spanish landscape are still present. The second political driver was the National Irrigation Modernization Plan approved in 2002 to modernize the irrigation scheme of 1,134,000 ha (including renewal of conveyance infrastructures and a shift to high efficiency application systems) to achieve some 2,100 Mm^3 of water savings by 2008, which entailed an investment of almost 7,000 million euros (López-Gunn et al., 2012a). However, the lack of understanding on trade-offs in water-energy efficiencies and possible rebound effects meant the plan had an estimated 65% lower water savings than planned and an increase of over 70% in farmers' energy bills. It also had some positive impacts in terms of agricultural physical and economic productivity and rural development (López-Gunn et al., 2012b).

Overall, Spain has a vulnerable position in terms of water, energy and food securities that will be exacerbated if a silos approach that neglects the several water-energy-food interconnections continues. In particular, decisions on the array of energy technologies to be promoted by mid/long-term energy roadmaps are now known to have important environmental and social externalities if water and food trade-offs are not taken into account in the decision making process. Momentum in water, energy and agricultural planning stages, when critical decisions and measures to define future roadmaps are on the table, bring an added urgency to further our knowledge on WEF interconnections, potential implications at the local and national scale and how these interconnections manifest in real cases. In addition these indicate the value of developing evidence based policy guidelines and recommendations that can effectively reach policy makers.

1.2. Thesis objectives

The overall aim of this thesis is to increase our knowledge on the water-energy-food nexus (WEF nexus) approach and its applicability for improved resource management. It takes the baton to address some of the critical nexus research challenges presented above, particularly: 1. clarification of the purpose and applicability of the 'WEF nexus approach', 2. knowledge generation through expert consultations, 3. development of practical cases with higher quality resolution data and trade-off accounting, and 4. knowledge and assessment of impacts of hydropower and other energy technologies on the water-environment spheres.

As a result, this thesis is underpinned by three main goals:

- First, an analysis and discussion on the different **definitions and frameworks for the WEF nexus approach**, reflecting on its rationale, purpose and potential applicability to put forward a proposal methodology to undertake WEF nexus analyses.
- Second, to study **trends on main variables and levels of uncertainty** within the WEF nexus based on a meta-analysis of the literature and expert consultations, with the aim to detect key nexus challenges and gather knowledge on critical uncertainty aspects.
- Third, through **applied case studies** zoom into relevant WEF nexus related problem areas, particularly the issue of WEF nexus trade-offs, by looking at two specific examples: the analysis of impacts from hydropower and the analysis of potential implications for water security from hydraulic fracturing.

The two first goals are of a more theoretical nature, aiming to advance in 'basic research' i.e. the conceptual frame around the nexus. The third goal aims to bring these advances and concepts to reality by applying and testing them in real cases, through 'applied research'. These main goals are materialized into five objectives developed throughout 6 chapters constituting the main body of this thesis.

Objective 1: Identification and analysis of global trends, most relevant knowledge gaps and areas of uncertainty on the WEF nexus. Application of a qualitative approach to cross check the predictions on the future evolution trends for certain variables with a high level of uncertainty with the vision of Spanish national experts using the Delphi methodology.

Objective 2. Description and analysis of the different frameworks proposed for the WEF nexus concept and approach, as well as reflection on its rationality, purpose and potential applicability.

Objective 3. Proposal of a methodology to perform WEF nexus analyses and application of this methodology at a basin scale, taking the Spanish Duero river basin as case study. This methodology will aim to guide the accounting of WEF nexus trade-offs, looking at the coordination of water, energy and food policies, identification of related conflicts and proposals for integrated solutions.

Objective 4. Elaboration of a case study to analyse the comparative cumulative contributions to water and energy security from hydropower, as well as the impacts the deployment of large and small scale hydropower at a basin scale. This objective is motivated by the intense international controversy about the sustainability of both large and small scale hydropower, and the extent to which it can be considered a sustainable energy option when deployed at large scale at basin scale. At the same time, it answers the call for more applied studies on the accounting and characterization of hydropower impacts at local scale, which has been identified as one of the nexus areas where research is most needed (Hoff, 2011; WWAP, 2014).

Objective 5. Analysis of the challenges for water security posed by the application of hydraulic fracturing techniques to produce non conventional gas. To perform this analysis, a comparison is made between two regions with different stages of development of the hydraulic fracturing activity: the state of Texas in the U.S., with an advanced and active hydraulic fracturing industry, and Spain as a case of recently emerging initiatives in a country within the European Union. This study aims to contribute with some analysis and reflections to the controversy over the possible expansion of the U.S. 'shale gas revolution' to the European - and particularly - in the Spanish context.

In order to help articulate and address the thesis specific objectives a series of research questions were formulated as presented in Table 1.1.

THESIS OBJECTIVES	RESEARCH QUESTIONS
Objective 1	1. What are the main global trends on the WEF nexus? 2. What are the key relevant knowledge gaps and variables where available data are scarce or uncertain? 3. What is the perception of experts on the potential future evolution of these variables?
Objective 2	4. What are the main conceptual frameworks defined to date for the WEF nexus? 5. Does the WEF nexus concept provide something new compared to other resource management approaches like the Integrated Water Resources Management Approach (IWRM)?
Objective 3	6. How could the WEF nexus framework be applied to a basin scale as an analysis tool to diagnose management conflicts and provide solutions?
Objective 4	7. How can the large scale development of large and small scale hydropower plants in a basin comparatively impact water and energy security and the integrity of river ecosystems?
Objective 5	8. What are the main water related and social challenges derived from the development of hydraulic fracturing in a region? 9. How do they vary in different legal and geographical contexts, i.e. Texas in the U.S. and Spain in Europe?

Table 1.1. Research questions for the different Objectives

1.3. Thesis outline and structure

The thesis is organized in seven chapters. Chapter 1 is devoted to introduce the research context and framework for the thesis, as well as to describe the thesis objectives, structure and methodologies. Chapter 2 provides an extended literature review of the emergence, evolution and present state of the Water-Energy-Food Nexus concept and approach, as well as an in depth analysis of the nexus driver trends and research lines. Chapter 3 presents the study on the future evolution of variables and particularly those which are more uncertain related to water, energy and food security from an expert perspective through the use of the Delphi methodology. Chapter 4 links to the conceptual description of chapter 2, to propose a methodology to develop a WEF nexus analyses aimed at improving natural resources management, and provides results from the application of this methodology to the Duero river basin in Spain. Chapter 5 gives an introduction to the international debate on whether hydropower can be considered a sustainable with potential to reduce water and energy conflicts in the future, and presents a case study that compares the contributions of large and small scale hydropower to regional water and energy security, as well as the cumulative impacts in the Duero river basin in Spain. Chapter 6 presents the last case study where the potential implications for water security of hydraulic fracturing are analysed comparatively in two regions with different contexts and development stages: the state of Texas in the U.S. and Spain, as a country in the EU.

Finally chapter 7 summarizes the conclusions and contributions of this thesis to scientific knowledge on the WEF nexus, and provides a series of recommendations and reflections on their potential applicability and policy guidance value. The relation between the research questions, thesis objectives and chapters is represented in Figure 1.4.

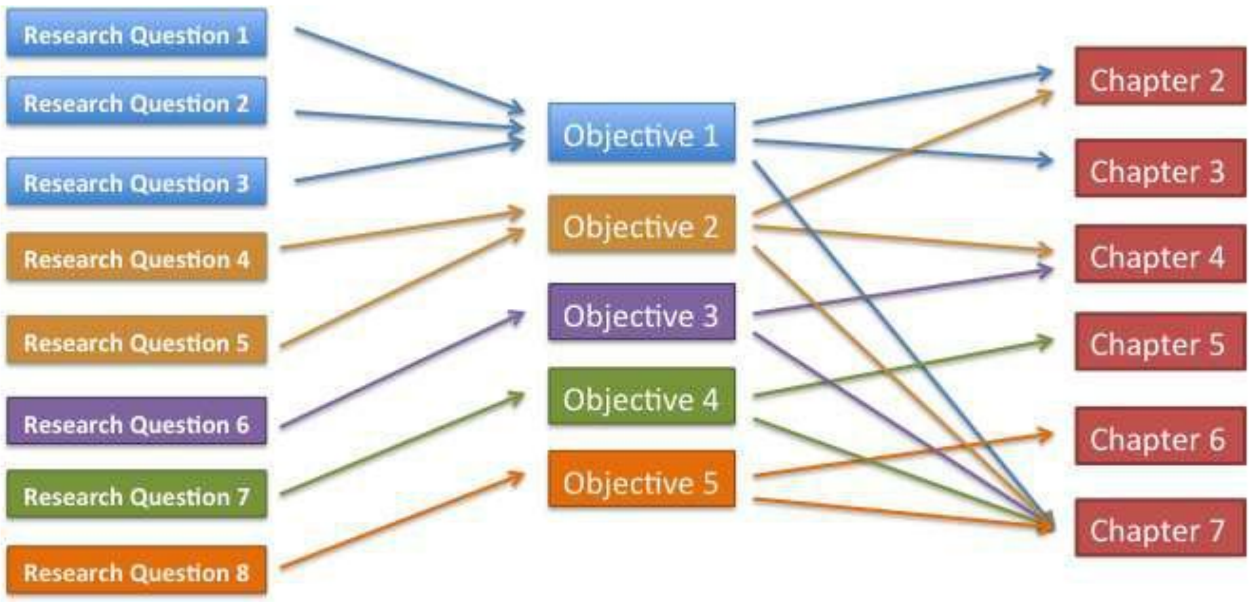

Fig. 1.4. Diagram of relations between thesis research questions, objectives and chapters

1.4. Materials and methodology

This section describes the materials and methods used in this thesis to address the research objectives and questions. These methodologies and the process followed for each research objective are further developed in the corresponding chapters (see Figure 1.4).

The process followed to address the different research objectives was similar for all the research questions posed (and corresponding research objectives). First, a selection of the methodology was made on the basis of the research question posed. Second, identification of data and information required for the specific research question and methodology, and identification of best data collection methodologies and available data sources. Third, data collection, analysis and interpretation and finally the drawing of conclusions.

1.4.1. Selection of applied case studies

As mentioned above, Objectives 3, 4 and 5 adopted an applied approach to the nexus. For this purpose three case studies were identified: the first was an integrated WEF nexus assessment at a basin scale; the second was a comparative assessment of cumulative impacts from large and small scale hydropower on environmental, water and energy security aspects in a basin with a large hydropower deployment; the third was a comparative analysis of the contextual framework and main water trade-offs related to hydraulic fracturing initiatives in the U.S. and the European/Spanish contexts.

An important aspect was the geographical scale to be selected for the case studies. This scale aspect is one of the main uncertainty issues identified in the nexus literature review – i.e. which is the best scale to adopt when dealing with WEF nexus issues. As discussed in chapter 2, different nexus studies have taken different scales, ranging from national to regional, basin or local scales (Newell et al., 2011; Opperman et al., 2011; Stillwell et al., 2011; Lawford et al., 2013). For two of the Objectives the basin scale was considered the most appropriate for two reasons: first water data generally constitute a key conditioning factor for nexus analyses. This is partly because energy and food accounting and resource flow data are more easily available in general at different levels (national level, regions), while water data is usually only available at the basin and maybe sub-basin scale. Second, the basin scale has also been recognized as the most suitable management unit when working with water issues as well as the appropriate size for water accountings (Molden, 2007).

With regards to the specific geographic location, Spain was selected for a number of reasons.

- First, due to its long tradition in water management, since Spain one of the first countries to institute river basins as the water management units, creating its first river basin authority in 1926 (the Ebro) and the Duero closely behind in 1927. The basin scale has now been adopted at European scale under the Water Framework Directive. Spain has an extensive history for a vast hydropower deployment, a strong tradition in irrigated agriculture and in many ways a silos approach to water, food and particularly energy management and planning, explained partly by its administrative set up. This - together with other emerging nexus issues like shale gas exploration - make Spain a perfect scenario to explore WEF nexus trade-offs, interrelations and cross efficiencies.
- Second Spain is currently in a policy period with many upcoming policy objectives in the energy, agriculture and water planning sectors (climate change adaptation plans, post 2020 energy roadmap, development and advancement of the 2015-2021 water plans, implementation of the CAP). In this context having more precise evidence and information on what the WEF nexus approach is, understanding the WEF nexus interconnections, what benefits nexus thinking can bring and how it can be applied, could help guide these policy processes.
- Finally, other factors like the language, networking, available resources to do the study and the proximity of the study sites supported this selection.

Within Spain, the Duero basin was selected as case study for two of the objectives (3 and 4) due to a series of characteristics.

- First, it is the biggest transboundary basin in Spain with an area of 98,073 km^2 from which 78,859 km^2 correspond to the Spanish part. It is one of the most representatives for the country since it gathers the same characteristic features: high rainfall variability, an important role of hydropower and agriculture in water use and a complex network of stakeholders.

- Second, 98% of the surface of the Spanish part of the basin is encompassed within one autonomous region, which facilitated energy and food data collection and allowed to make fair geographical approximations to the region when data at basin scale was not available.
- Third, there was a high commitment for collaboration and support from several members of the Duero River Basin Authority, which facilitated the gathering of information, data and existing knowledge on the area.

For Objective 5 on the hydraulic fracturing challenges for water security, a state within the U.S., particularly Texas, was selected to establish the comparison with the Spanish case for several reasons.

- First, the U.S. and in particular the state of Texas has had the longest experience and knowledge in hydraulic fracturing. The contrast from comparing two regions – Spain as emerging and the U.S. as well established – offered considerable policy learning opportunities.
- Second, the differences and similarities between the two regions in terms of size, geographical conditions (e.g. water scarcity), demographic conditions and legal framework gave room for comparative analysis.
- Third, benefits from a short research stage between August and November 2014 at the Oklahoma Water Survey under the supervision of Dr. Robert Puls gave the opportunity to gather valuable information for the comparative analysis. In addition, chapter 6 (which addresses Objective 5) has been developed in collaboration with Regina Buono, Baker Botts Fellow in Energy and Environmental Regulatory Affairs at the Center for Energy Studies in Houston (Texas), who compiled the information for the Texas case; and Elena López Gunn, thesis director.

1.4.2. Data collection and analysis methods

Both quantitative and qualitative data collection methods were required to accomplish the thesis objectives. The type of data collection method and sources used depended on the type of information and particularities of the specific research objectives and questions. In general, existing literature and databases were used to obtain quantitative data, whereas literature and semi-structured interviews were used to obtain qualitative information, finally the Delphi method was applied to gather expert knowledge in a structured format that allowed both qualitative and quantitative analysis.

Some of the data collection activites detailed below were undertaken in the framework of two research projects in which the PhD candidate was engaged during the PhD research.

- *Elite expert interviews* and the *Delphi study* (see sections 1.4.2.2 and 1.4.2.4) were part of the activities undertaken by the 'Water Node' research team at Complutense University for Repsol's Technology Centre '*Heredera'* project. The design and conduction of the interviews as well as the conduction of the Delphi survey were performed by the UCM's Water Node, composed of Beatriz Mayor (PhD Candidate), Roberto Rodríguez and Virginia Alonso de Linaje. The analysis of results, elaboration of a scientific publication and adaptation as a thesis chapter were undertaken by the PhD candidate.

- *Expert interviews and online survey* (see section 1.4.2.3) were done as part of the European Commission, DG Research and innovation poject *'Study on the Nexus between water, energy and food security: research and innovation in the context of climate change'*, aimed to analyse the key emerging issues for research and innovation in the Nexus and to provide recommendations for the strategic planning of the Horizon 2020 program and future research and innovation. The results from these interviews were used to further develop the initial results for Objective 1 and complement the picture on WEF nexus trends, challenges and opportunities presented in chapter 4.

1.4.2.1. Use of metrics, indicators and data collection from literature and databases

The consultation and review of existing literature was used as a documental base at all its stages of the research. The extensive literature review provided the main documentary basis for chapters 1 and 4, to address Objective 1 and 2 of the thesis on global nexus trends and frameworks for analysis[2]. This also provided the basis and baseline to develop the other thesis chapters and case studies. The materials reviewed include both written materials (reports, scientific literature, materials available online, conference presentations, etc.) and audio materials obtained during the attendance to several conferences, seminars and webinars. A list of the references used is provided at the end of the thesis, and a complete list of publications reviewed and conferences attended for this thesis is provided in Annex 1.

For the case studies developed to address Objectives 3 and 4 on a nexus analysis at basin scale and the water and energy security impacts from small vs large hydropower, in the Duero basin, a methodology was developed which consisted in applying a series of accounting metrics and indicators. Further details on the specific indicators used in each case are provided in the corresponding chapters. Data was mainly obtained at basin scale, from the river basin authority databases, including the river basin management plans, digital information platforms (Mírame Duero, Iberpix), published reports and fact sheets; at national scale, from the national energy plans and regional energy statistics; and at regional level, from the regional plans for bio-energy and rural development. For Objective 4 on hydropower additional data was requested: local bio-energy plants, biofuel producers and electricity and water supply companies.

1.4.2.2. Data collection through semi structured qualitative interviews

Semi structured qualitative personal interviews were used to gather qualitative information for the Objective that focused on the main nexus trends (Objective 1) and hydraulic fracturing (Objective 5). A format of semi-structured interviews was adopted, which consists of posing open questions to the interviewees giving them space to extend their answer. Expert interviews provided the following advantages:

- Interviews provide the opportunity to generate rich qualitative data;
- The natural language use by participants was considered essential in gaining insight into their perceptions and values;

[2] Objective 1: Identification and analysis of global trends, most relevant knowledge gaps and areas of uncertainty on the WEF nexus. And Objective 2**.** Description and analysis of the different frameworks proposed for the WEF nexus concept and approach, as well as reflection on its rationality, purpose and potential applicability

- The interview format gives the opportunity to the interviewee to bring additional aspects considered relevant and not included in the questionnaire, thus allowing for the identification of possible unconsidered aspects.

According to the type of target information required, two different types of interviews were designed for Objectives 1 (nexus trends) and Objective 5 (hydraulic fracturing): elite interviews in the first case and stakeholder interviews in the second case.

Elite interviews

Elite interviews were designed for Objective 1 and consisted in the conduction of face to face interviews to select experts on the WEF nexus to address research questions 1 and 2 on the identification of main WEF nexus trends and areas of uncertainty (see Figure 1.5). The results from these interviews also helped to validate the results from the Delphi questionnaires, as described in chapter 3. These interviews were conducted under the framework of Repsol's Heredera project, which set the following criteria for the selection of experts: 1) high expertise on all or some of the WEF axis (water-food, energy-food, water-energy); 2) possibility to conduct face interviews of between 1 and 1.30 hours duration; 3) the number of interviewees had to account for 5 Spanish experts and 1 international expert. The final questionnaires used in the interview and the list of experts interviewed and their affiliations are provided in annexes 2 and 4.

Fig.1.5. Elite interview to Emilio Custodio. From left to right Emilio Custodio (Emerithus professor at Technical University of Catalonya), Roberto Rodríguez Casado (project researcher), Beatriz Mayor (thesis author) and Virginia Alonso de Linaje (project researcher).

Stakeholder interviews

Stakeholder interviews were designed to collect qualitative information for Objective 5 (hydraulic fracturing). The purpose of the interviews was first, to gain information on the regional status of hydraulic fracturing activities and technical procedures and permissions required, and second to gather the perception of the different stakeholders on the potential benefits and risks from the activity as well as the main social issues.

On this basis, two sets of interviews were conducted, one in Spain and one in the U.S. The U.S. Interviews were conducted during the research stage period at the Oklahoma Water Survey/Oklahoma University. Similar questionnaires were used for both sets with some variation depending on the type of stakeholders. All questionnaires included questions on the most relevant uncertainty aspects regarding potential risks and trade-offs from hydraulic fracturing for water resources. The questionnaires were elaborated on the basis of a review of existing literature and issues raised in conferences, seminars and debates attended on the topic (see annex 1) and both the Spanish and the English versions are provided in annex 6. The selection of interviewees was made based on a snowball approach whilst also aiming to include representatives from most of the stakeholder groups. All the interviews were held face to face except one done by telephone. The list of actors interviewed, their affiliation and type of stakeholder is provided in annex 3.

1.4.2.3. Expert interviews and online survey

This first round of 6 interviews was then built upon with a second round of 18 expert interviews, which was also complemented by an online survey through Survey Monkey to 72 experts[3]. The results from these interviews have fed the nexus trends and drivers' description in chapter 2 and the final conclusions. The Interview script of both the face to face interviews and the Survey consisted of 15 questions which 10 were open and 5 were closed (see annex 7). The topics included in the closed survey monkey online survey were derived from the literature review on nexus studies and the Millennium database[4].

The interview script was organised in the following sequence:

- First, a series of general questions on the nexus,
- Second, a series of open questions looking in turn at each part of the nexus (water/energy; energy/food and food/water),
- Third, a group of additional targeted questions on the different relative weight of each part of the nexus, the role of climate change, potential disruptive events and leaving room for additional comments from the interviewees.

A total of 18 interviews were undertaken in person or by teleconference, whereas the remaining 72 replies (out of 86 total replies) were collected via Survey Monkey with the same interview script. The answers were analyzed anonymously. For project confidentiality purposes, the identity and profile of the experts participating is kept anonymous.

1.4.2.4. The Delphi method

The Delphi method was used to obtain information in a context with a high degree of uncertainty on the possible evolution of key water and energy variables based on the perception of experts, in order to address the Objective 1 on Nexus trends. The process and results of applying this methodology are presented in chapter 5.

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[3] The first phase interviews were part of the Repsol Heredera project, the second phase interview were part of an EU DG Research funded project on the nexus to get expert opinion on the main nexus topics and cross-check the key issues identified in the literature review.

[4] The Millennium Database is an online knowledge repository created as part of The Millennium Project. This project is aimed to improve thinking about the future and make that thinking available through a variety of media for feedback to accumulate wisdom about the future for better decisions today. It is composed of a network of knowledge nodes from all over the world.

www.millennium-project.org

The Delphi method is a well known social research technique aimed at obtaining a reliable opinion from a set of experts (Dalkey et al., 1963). This is a method of structuring communication within a group of people who can provide valuable knowledge for solving a complex problem (Linstone & Turoff, 1975). It was conceived in the 1950s for military purposes and has been used in academic and business spheres. It has been mainly applied as a technique for planning and consensus in uncertainty situations where it is not possible to use other methods based on objective information.

Its main characteristics are as follows (Dalkey et al., 1963):

- It is an iterative process. The experts must be consulted at least twice on the same question, so that they can rethink their reply, assisted by the information received from the opinions of other experts.
- It keeps the anonymity of participants' replies, as these go directly to the coordinating group. This means one can undertake a process of group work with experts who do not coincide in either time or space and also seeks to avoid the negative influences that personality related factors may have on the individual replies.
- Controlled feedback. The exchange of information between experts is done through the coordinating group, thus eliminating any irrelevant information.
- Statistical response of the group. All the opinions form part of the final reply. The questions are asked in such a way that a quantitative and statistical treatment of replies can be made.

These characteristics compensate some of the main disadvantages of group judgements obtained from direct interaction techniques. Nevertheless, in spite of its broad utilization, this technique presents a number of acknowledged methodological weaknesses that have been described in previous studies (Gordon & Hayward, 1968; Sackman, 1974; Linstone, 1975; Landeta, 2006).

The main methodological limitations include the following:

- First, the basic source of information for this technique is expert judgement, which can be subjective or biased. This can be reduced by a proper selection of experts and good knowledge management. In this study, experts were selected on the basis of the known experience in water-energy interconnections, aiming for a diverse representation of stakeholders to minimize bias. Meanwhile, an in-depth literature study was made to complement and contrast results.
- Second, it assumes consensus as an approximation to reality.
- Third, interaction among experts is real though limited and thus anonymity impedes the social rewards provided by other's acceptance of own responses. This was overcome by keeping anonymity of responses but making public the names of the participants with their consent, thus encouraging their public recognition as experts.
- Fourth, it is a time demanding technique for experts, which does not consider possible interrelation of future planned events. To compensate experts for their efforts, experts were sent a copy of the final report and made aware of all positive outcomes of the project.

On the whole, advantages such as its flexibility and simplicity have proved to outweigh the disadvantages, as shown by the growing number of examples of successful application in different geographical and thematic contexts, within the academic and professional spheres, where expert knowledge has been recognized as the best available knowledge (Gupta & Clark, 1996; Landeta, 2006).

The usual stages of a Delphi process are described by Fowles (1978) as the following:

1. Formation of a team to undertake and monitor a Delphi on a given subject.
2. Selection of one or more panels to participate in the exercise. Usually, the panellists are experts in the area to be investigated.
3. Development of the first round Delphi questionnaire
4. Testing the questionnaire for proper wording (e.g., ambiguities, vagueness)
5. Transmission of the first questionnaires to the panellists
6. Analysis of the first round responses
7. Preparation of the second round questionnaires (and possible testing)
8. Transmission of the second round questionnaires to the panellists
9. Analysis of the second round responses (Steps 7 to 9 are reiterated as long as desired or necessary to achieve stability in the results.)
10. Preparation of a report by the analysis team to present the conclusions of the exercise

The particularities introduced for the purpose of this thesis study and the processed followed are presented and further detailed in chapter 5. The original questionnaires contained 17 quantitative questions that asked for a prediction to three time horizons (2020, 2030 and 2050) and a justification for the answer. Experts were also asked to rate their level of expertise in each question. The questionnaires were submitted by email to the experts, who resubmitted their responses on the same document. The final version of the Delphi questionnaires and the list of experts who participated in the survey with their affiliations are provided in annexes 2 and 5.

The analysis of the questionnaires consisted of three parts:

Quantitative analysis

Quantitative questions were analysed by taking the results from the second round considered by the experts as ‘final responses’. A series of statistics were estimated, including mean, median, and standard deviation, and the results were interpreted based on the mean and the standard deviation values, since the inclusion of anomalous predictions incorporated the probability of occurrence of disruptive conditions that may change the trend line, as perceived by experts.

Qualitative analysis

Qualitative comments were grouped in function of the quantitative response (increasing trend, decreasing trend, on the average, anomalous) and summarized to explain the different reasons provided to back up the resulting average trend and the possible factors that may influence it.

Analysis of performance

An analysis of the differences between the first and the second round and the trends showed by experts in the modification of their answers between rounds were also analysed and commented. The possible relationship of these trends with the level of expertise reported by the experts was also analysed.

CHAPTER 2

STATE OF THE ART CONCEPTS AND TRENDS IN NEXUS RESEARCH

Chapter 2. State of the Art: concepts and trends in Nexus research

2.1. Historical evolution of the WEF nexus concept

2.1.1. Origin, evolution and milestones

The water-energy nexus concept was born in the south-western United States, where the first studies emerged raising concerns on the implications of the interdependencies between water and energy (IAEA, 1977; Gleick, 2003; Cohen et al., 2004; Hoffman et al., 2004), first from an economic point view (hidden costs) and later as a possible threat to water and energy security, followed by the first water-energy roadmap (NETL, 2009). Later on, this concept started to spread, fostered by important disruptive events such as the threat to thermal and nuclear power production during the severe drought in Europe, and particularly hard in France in 2003, when urban water supply was prioritized over other uses; or the nuclear accident of Fukushima in 2011, where a tidal wave threatened to cause the biggest nuclear accident after Chernobyl. Some of the most relevant milestones driving the emergence and evolution of the water-energy-food nexus vision are presented in table 2.1.

Milestones for the emergence of the WEF Nexus vision
Recognition of climate change problematic (more frequent heat waves, prolonged droughts) and the related risks for energy security (thermal cooling, hydropower production) (2003-2011)
Nuclear disasters: Chernobyl (1986) and Fukushima (2011)
Oil spills into the ocean and development of bio-remediation (1986-
2010) Rise of biofuels and food markets inflation in 2006-2007
International recognition of the WEF Nexus (2008-2011)

Table 2.1: Milestones for the emergence of the WEF Nexus vision.

In 2011 the first International Conference on the nexus was celebrated in Bonn, Germany, where a third element, food, was recognized as the third axis of a triangle whose intrinsic interconnections have direct impacts on water, energy and food security (Hoff, 2011). The WEF nexus concept gathered momentum with several important international conferences such as the 6th World Water Forum, the Green Week Conference 2012, the Rio +20 Conference and the Stockholm's World Water Week, where the water-energy-food nexus was always present. By the end of 2012, the International Energy Agency set a precedent by including for the first time a chapter on water aspects in their annual 'World Energy Outlook' scenarios (WEO, 2012). This spurred a series of regional water-energy assessment studies where - not only water for energy, but also energy requirements for providing water services - were further characterized (Yates et al., 2013; Water in the West, 2013; Hadian & Madani, 2013). It also hosted the birth of two of the biggest initiatives to address, regularize and further develop the issue: the World Bank's *Thirsty Energy* initiative (Rodríguez et al., 2013) and the W4EF initiative (Bellet, 2014). All this background served as a basis for information and debate that would find its climax in 2014, the UN International year of Water and Energy, starting with the UN International Conference for preparation of the World Day of Water and Energy in Zaragoza (Spain). On March 21st the *UN World Water and Energy Day* was celebrated all over the world. The main event was held in Tokyo (Japan), where the 4th UNESCO's World Water Development Report on Water and Energy was launched, followed by a series of parallel worldwide side events occurring simultaneously. Within this intense debate, some of the most important topics discussed referred to the lack, dispersion and imprecision of data for both water and energy accountings; poor knowledge on nexus interconnections and their consequences, as well as on the interactions with other driving forces, such as food security or climate change; and how to best deal with these problems through the implementation of integrated management policies. This last aspect was especially reinforced during the International Conference on Sustainability in the Water-Energy-Food Nexus celebrated in Bonn in spring 2014, when a call for action for policy makers, practitioners and researchers to start developing coupled water-energy-food strategies was specifically made (GWSP, 2014).

The shift led to a strategic year, 2015 which constitutes an end of cycle year in which the Millennium Development Goals Agenda comes to an end and critical discussions, decisions and outcomes to frame the future sustainability roadmap are to be taken in the international arena. The year will host four particularly outstanding international events: the Post 2015 Sustainable Development Agenda, the 3rd UN World Conference on Disaster Risk Reduction (DRR), the United Nations Framework Convention on Climate Change (UNFCCC) COP21 Conference and the 3rd International Conference on Financing for Development. The water-energy-food nexus is directly or indirectly present in these four processes given the important role of water, energy and food issues in sustainability, natural disasters, climate change and financial needs for development.

The Nexus in the 3rd World Conference on Disaster Risk Reduction

The 3rd United Nations World Conference on Disaster Risk Reduction celebrated in March 2015 in Sendai (Japan) had the final aim to come up with a consensual framework on Disaster Risk Reduction for the period 2015-2030, as a continuation of the Hyogo Framework for Action developed in 2005. The 'Hyogo Framework for Action' has served as an important instrument for raising public and institutional awareness, generating political commitment and catalysing actions on disaster risks reduction (UN, 2015a). However, possibly due to the impacts of emerging anthropogenic climate change, disasters have increased in frequency and magnitude in the last ten years - and experts forecast will continue to do so-, causing a rise on disaster-related losses with significant short and long term economic, social, health, cultural and environmental impacts (UN, 2015a). This has raised concerns over the need to develop a strong risk reduction framework and raise efforts and investments to reduce vulnerability and create preparedness.

Provided that 90% of global hazards are water related (WWAP, 2012), many of them constitute a threat to water and energy infrastructure (see the Fukushima case for instance), and most of them have negative consequences on food production. Therefore the WEF nexus is intimately connected and should play an active part both within the discussions and the solutions to address disasters´ risk. Despite not being expressly mentioned in the Conference outcome document (UN, 2015a), the nexus is inherent in the importance given to agriculture, water and infrastructure related risks, and the commitments to 'promote the resilience of new and existing critical infrastructure, including water, transportation and telecommunications infrastructure […]' and 'The development, strengthening and implementation of relevant policies, plans, practices and mechanisms need to aim at coherence, as appropriate, across sustainable development and growth, food security, health and safety, climate change and variability, environmental management and disaster risk reduction agendas' (UN, 2015a). However, in this case the extent to which a holistic view of the intersections between the three axes (water, energy and food) has been considered to build the Disaster Risk Reduction framework is not so clear.

The Nexus at the UNFCCC COP 21 Conference

The disappointing results of the 2009 United Nations Framework Convention on Climate Change COP20 left a bitter taste in the International Community regarding future roadmaps to stop climate change. In view of the alarming results from Intergovernmental Panel on Climate Change (IPCC)'s 5th report, which warns about the disastrous consequences of a global temperature rise over 2 C for people, the environment and economies – something that will probably occur by 2050 if the current GHG emission trends continue - the United Nations has convened the 2015 United Nations Framework Convention on Climate Change (UNFCCC) COP21 that will take place in December in Paris. This international Conference has the aim to achieve for the first time a universal, legally binding agreement to combat climate change effectively and boost the transition towards resilient, low-carbon societies and economies (COP 21, 2015). The agreement should cover both mitigation and adaptation strategies and take into account the capacities and needs of all countries, and would enter into force in 2020. A parallel objective will be the facilitation of financial resources to address climate change and sustainable development through the annual mobilization of $100 billion by developed countries from 2020, coming from both public and private sources. These funds will be passed through different mechanisms like the Green Climate Fund, which has been injected with an initial capital of $10.2 billion (COP 21, 2015).

Climate change and the WEF nexus are closely linked and hold complex cause-effect interrelations. Talking about mitigation means talking about reducing GHG emissions, which come in a great part from the energy sector, particularly from fossil fuels. Meanwhile, as mentioned before, climate related hazards seriously threaten water, energy and food security, while adapting to climate change involves finding strategies to manage and use resources in a way that maximizes the capacity of communities to react to hazardous situations and overcome them. It is increasingly acknowledged that to undertake mitigation and adaptation actions in the energy, agriculture, land use and industry sectors, a nexus approach can support the identification of synergies, conflicts and opportunities to optimise mitigation (and adaptation) options, and help achieve higher capacity to react through effective coordination across sectors (Bellfield, 2015). The nexus will thus be an important topic to consider in the discussions and final Conference outcomes.

The Nexus at the 3rd International Conference on Financing for Development

The 3rd International Conference on Financing for Development has been convened by the UN in Addis Ababa (Ethiopia) in July 2015 to address the financial challenges for sustainable development. It seeks to promote national financing frameworks to support cohesive national and self-sufficient sustainable development strategies, in order to eradicate poverty through facilitating sustainable economic growth and industrialization, social inclusion and environmental sustainability (UN, 2015b). This will be supported by an enabling international economic environment, including several factors like coherent world trade, monetary and financial systems, support to technology development and transfer, capacity building, and strengthened global economic governance (UN, 2015b).

It has been acknowledged that the main financial challenge facing the WEF nexus and sustainable development are the substantial investments required to develop and upgrade new and existing energy and water infrastructure. Public investment will play a key role to fill this gap, through the development of financing institutions and incentives to private investment; but private involvement will also be required for the upgrade and transition of energy infrastructure towards a clean energy technology system

(UN, 2015b). There is an invitation for countries to explore innovative financing modalities and instruments, like carbon pricing, taxes for fuels, enabling regulations for renewable energies or smart agricultural subsidies. Meanwhile, the water sector will need to efficiently promote water projects to attract the interest of donors, since funding constraints in the sector seem to be more linked to a business case failure than to a lack of potential funding (UNW-DPAC, 2015a). Science, technology, innovation and capacity building are again identified as critical to achieving sustainable development, and thus investment streams will need to be allocated to strengthen them.

The Nexus at the Post 2015 Agenda for Sustainable Development

The United Nations summit for the adoption of the post-2015 development agenda will be held in September 25-27 2015 in New York and convened as a high-level plenary meeting of the General Assembly. This event is the end result of years of work and discussions to set the Post 2015 Agenda on Sustainable Development and set the final list of Sustainable Development Goals (SDGs) to be met by 2025.

The nexus has an inherent role in this process, since energy, water and food are at the core of sustainable development, as well as an essential condition for human well being and minimum living standards, and is amongst the top priorities within the Post 2015 debate (UNW-DPC, 2015). Some guiding principles of the nexus approach are to promote sustainable and efficient resource use to ensure access to resources for the most vulnerable and to maintain healthy and productive ecosystems (Hoff 2011), which are in line with many SDG proposals (SEI, 2014).

Particularly, achieving universal access to safe drinking water, basic sanitation and modern energy services has been one of the greatest challenges during the MDGs decade and, despite the tangible progress, it still remains a key target to be continued along the SDGs implementation period. Within the preliminary proposal of SDGs, water, energy and food challenges are addressed in several targets. Particularly in the case of water, a specific goal has been devoted to address not only the Water Sanitation and Hygiene (WASH) sector, as the MDGs did, but all the different dimensions of water including water quality, transboundary waters, or integrated water management.

SDG targets that include water, energy and food issues as identified by SEI (2014) can be compiled into three main topic groups:

- Ensuring water, energy and food access and supply security
- Increasing sustainability in the management and use of resources through integrated governance and rising efficiency
- Reducing risks and increasing resilience against climate change

Within these topics, four outstanding words that illustrate the core WEF challenges and goals could be highlighted: *security, efficiency, sustainability* and *resilience*.

The SDGs Agenda also puts great focus on the means of implementation for action in the achievement of the SDGs. Essential conditions for successful implementation involve the financing issues and the related need for public-private partnerships and resource mobilization, the appropriate pricing of energy and water services and its potential to help close financial gaps, the indispensable role of capacity development, the relevance of adopting bottom-up and participative governance approaches and the promising contributions from technology and innovation (UNW-DPAC, 2015a). All these aspects are also essential to advance in the implementation of a nexus approach, to overcome nexus challenges and to attain those four magical words towards sustainable development and enabling a future.

Now reaching the end of 2015, the WEF nexus remains a trend topic gathering increasing attention. An array of working groups and initiatives are emerging within important international organisms and research institutes such as the World Energy Council, the OECD, UNU Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), the Texas A&M University/Future Earth, Global Water Operators' Partnerships Alliance (GWOPA), UNECE/FAO, the UK government or the Food Energy Environment and Water Network (FE2W), among others.

Some of the most important recent conferences on the WEF Nexus are presented in table 2.2.

RECENT REMARKABLE CONFERENCES ON THE WEF NEXUS
Connecting the Dots 2015. The Food, Energy, Water, and Climate Nexus. Friday, Stanford University, U.S. (April 17, 2015).
Dresden Nexus Conference (DNC 2015) ‘Global Change, Sustainable Development Goals and the Nexus’, UNU Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES), Dresden, Germany. (25–27 March, 2015)
International Conference on Water, Energy, and Food Nexus for Sustainable Development. SEA-EU-NET Partners in Science. Pattaya City, Thailand (November, 19-21, 2014)
What works at the nexus? The Nexus Network. London (November, 27, 2014)
Global Forum on Environment: New Perspectives on the Water-Energy-Food-Nexus. OECD. Paris, France (November, 27-28, 2014)
IWA World Water Congress & Exhibition, Lisbon/Portugal (September, 21-26, 2014)
Stockholm World Water Week 2014. SIWI. Stockholm, Sweden (August 31- September 5, 2014)
International Conference on Water-Food-Energy Nexus in Drylands: Bridging Science and Policy. OCP Policy Center in partnership with the Barcelona Centre for International Affairs (CIDOB), King’s College London and Texas A&M University. Rabat, Morocco (June 11-13, 2014)
International Conference Sustainability in the Water-Energy-Food Nexus. GWSP. Bonn, Germany (May, 19-20, 2014)
African Utility Week, Panel: Water-Energy-Food nexus. Cape Town, South Africa (May 13-14, 2014)
Connecting the dots 2014: The Climate, Energy, Food, and Water Nexus. Stanford University. California, U.S. (April 18, 2014)
The Water-Energy Nexus: Sustainability and Global Challenges. A U.S.-China EcoPartnerships conference organized by New York Institute of Technology and Peking University. Beijing, China (April 17, 2014)
Nexus 2014: Water, Food, Climate and Energy Conference. Water Institute – University of North Carolina, Chapel Hill, U.S.A. (March 3-7, 2014)
World Future Energy Summit, Abu Dhabi, UAE (January 21, 2014)
OTHER RELATED RELEVANT INTERNATIONAL CONFERENCES
United Nations Framework Convention on Climate Change (UNFCCC) COP 21 Conference, United Nations, Paris, France (November 30 – December 11, 2015)
United Nations Summit for the adoption of the Post-2015 Development Agenda, UN General Assembly, New York, U.S. (September 25 – 27, 2015).
3rd International Conference on Financing for Development, United Nations, Addis Ababa, Ethiopia, (July 13-16, 2015)
7th World Water Forum, Government of Korea, Daegu & Gyeongbuk, Republic of Korea (April 12-17, 2015)
3rd UN World Conference on Disaster Risk Reduction (DRR), United Nations, Sendai (Japan) (March 14-18 2015)

Table 2.2: Most recent conference related to the Water Energy Food Nexus

2.1.2. A succession of theoretical frameworks

Since the official recognition of the importance of the nexus during the Bonn Conference in 2011, there has been a succession of attempts to build a comprehensive conceptual framework that clearly defines the Nexus approach and its functionality, with variations depending on the lenses and scope of the proposing entities.

A first conceptualization was proposed by Hoff (2011) after the 2011 Bonn Nexus Conference, defining the nexus as '*interrelations between water, energy and food*', and the nexus approach as '*an approach that integrates management and governance, reduces trade-offs and builds synergies across sectors and scales*'. This definition has been enhanced with an aim to '*increase water security as a driver for energy and food security*' (WEF, 2011) and more completely described as '*a decision making framework which employs systems thinking to identify cross-sectorial impacts (externalities), explore feasible trade-offs and help policy makers achieve greater policy coherence as efforts are made to move development pathways which are resource efficient, equitable and sustainable*' (UNSGAB, 2014). The conceptualization made by the World Energy Forum (WEF, 2011) has been argued to lean on a resource economy rationality (Benson, 2015), since its formulation was mainly driven by international private actors who envisioned a series of opportunities and overall constraints to their businesses (Allouche et al., 2014; Muller, 2014).

The concept has later been further developed towards socio-ecological systems thinking, with frameworks aimed at analysing and understanding the trade-offs and synergies, improving resource governance and ensuring future water, energy and food security across scales and regions in a sustainable way (Allouche et al., 2014). Meanwhile, other criticisms have come from the fact that only focussing on the water-energy-food triangle (and assuming that climate change is considered as an external driver influencing the nexus), the critical sphere of nature or ecosystems is left behind, invalidating it as a possible pathway towards sustainability (Muller, 2014). *'How can hydropower be understood as a threefold solution if the environmental requirements and impacts are not accounted for?'* (Muller, 2014). This drawback is addressed by more ecosystems-focused frameworks like the one by the International Institute for Sustainable Development (IISD) (Bizikova et al., 2013) or UNEP (Boelee et al., 2014). In summary, although all the conceptualizations have a common base, there is not a unified and acknowledged definition of the WEF nexus concept and approach (Benson et al., 2015).

In 2013, the IISD published a study making a comprehensive review of the frameworks proposed to that date, as a preliminary for the presentation of their own framework (Bizikova et al., 2013). More recently, the United Nations Economic and Social Commission for Western Asia (ESCWA) has published a working paper with an updated review of the main frameworks proposed so far (ESCWA, 2015). Based on those reviews with some additions, a sequential description of the main Nexus frameworks and their conceptualizations is presented here.

Bonn 2011 framework

Purpose. To give the first representation of what should be a 'nexus oriented' approach considering water-energy-food interrelations, in order to promote better informed resource management for better security (Hoff, 2011).

Axes and variables considered. It considers the three axes - water, energy and food security – to be dependent on water availability, and also influenced by external variables: global trends (urbanization, population growth, climate change), governance, finance and innovation issues, as shown in Figure 2.1.

Action needed. It considers action needs to be taken in the social (increased access and equity, capacity building), economic (economic incentives, resource productivity), environmental (ecosystem services valuation and conservation) and governance (coherence and efficiency) spheres.

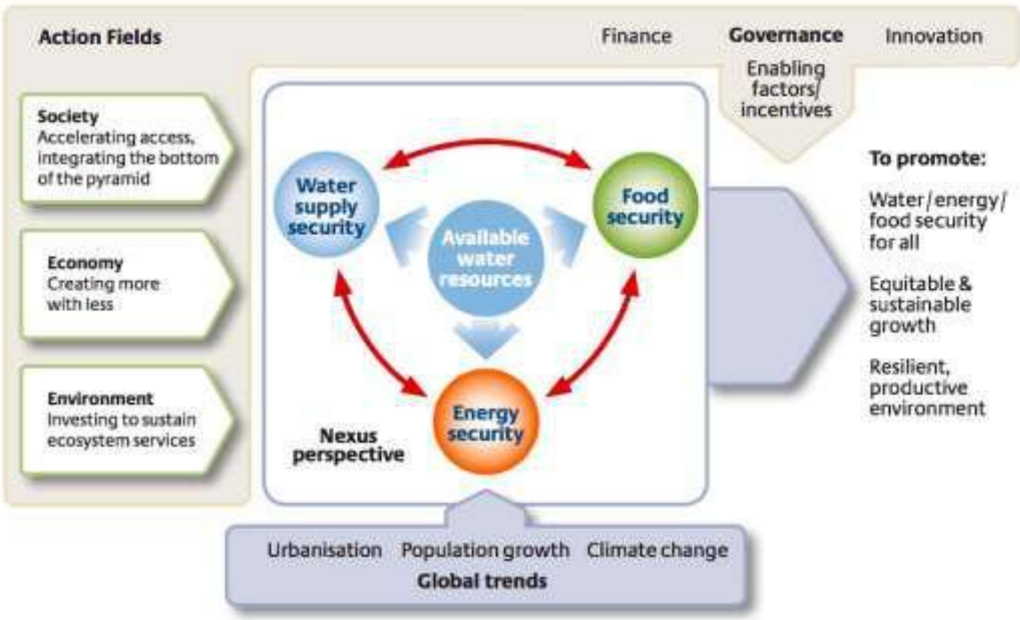


Fig. 2.1. Bonn 2011 framework. Source: Hoff, 2011

World Economic Forum 2011

Purpose. It is a risk-based framework aimed at supporting decision-making in the understanding of risks derived from the WEF interconnections and in developing response strategies (WEF, 2011).

Axes and variables considered. It considers the WEF nexus with its three axes as a global risk area that can lead to geopolitical conflict, and is also influenced by other global risks like *global governance failures* and *economic disparity*, as well as by external drivers like *population growth* and *environmental pressures*. The intensity on the production of each of the resources affects the other two, leading to resource shortages and social unrest and even to water, energy and food crisis, as shown in Figure 2.2.

Action needed. Areas proposed where action should be needed include the social (community empowerment), economic (resource pricing, financial innovation), technology innovation and political (multi-stakeholder planning, infrastructure development) spheres.

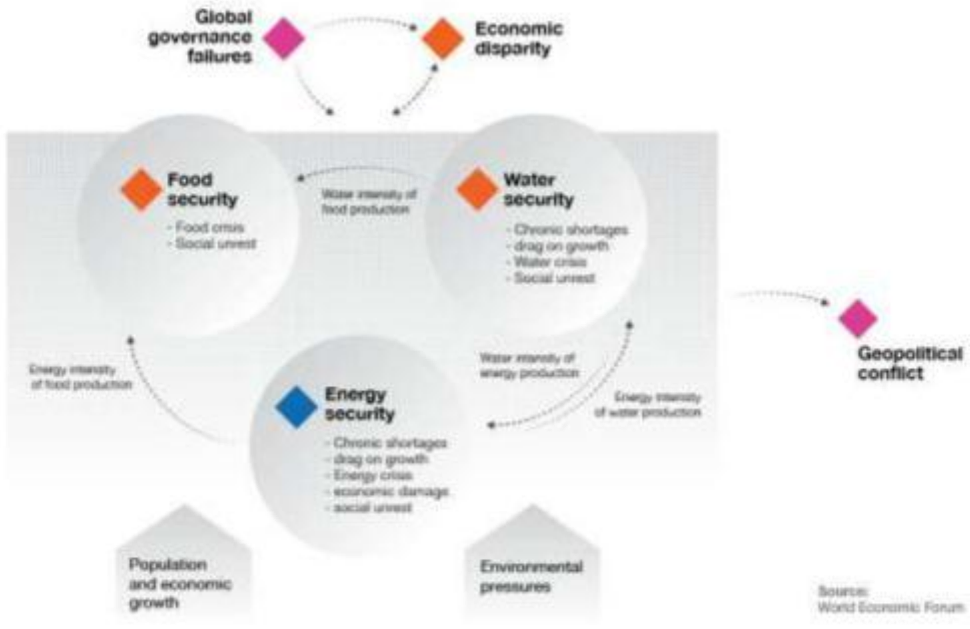


Fig. 2.2. World Economic Forum framework. Source: WEF, 2011

International Centre for Integrated Mountain Development (ICIMOD) 2012 and United Nations Economic Commission for Europe (UNECE) 2013

Purpose. A framework more centred in the relationship between the WEF nexus and ecosystems services and goods was developed by ICIMOD for the Hymalayan region (ICIMOD, 2012), followed by a very similar approach presented by UNECE (UNECE, 2013). Both have the purpose to emphasize the importance of ecosystem services and their contributions to water, energy and food security, as well as their vulnerability to an incoherent management of water, energy and food resources and interconnections, as shown in Figure 2.3.

Fig. 2.3. International Centre for Integrated Mountain Development framework. Source: ICIMOD, 2012

Axes and variables considered. They consider the three axes – water, energy and food – converging in resource security and with external contributions from ecosystems and their services,

Action needed. Actions proposed are mainly oriented to a better management of ecosystems (restoration of natural water storage capacity and promotion of natural and social values), with a specific emphasis on transboundary management in the case of UNECE (2013).

European Development Report (EDR) 2012

Purpose. The report puts into question the traditional world's approach to natural resources and claims for a new approach to demand, supply, efficiency and resilience of natural resources management that applies integrated solutions (EDR, 2012).

Axes and variables considered. It combines the water and energy axes with land as a third element of the triangle. It then reflects competition for the three resources from different users and technology types.

Action needed. It highlights the important role of three players (public sector, private sector and regional and global players) and identifies five key areas for action: reducing the environmental footprint of consumption, innovation in agriculture and renewable energy, a policy and institutional reform towards integrated management, inclusive and fair land policies and appropriate resource pricing.

Transatlantic Academy 2012

Purpose. To identify the challenges, dangers, and opportunities that will arise from the nexus of land, energy, food, water and minerals for the transatlantic community, with the aim to play a role in preventing the severe market disruptions and increased chances of violent conflict at interstate and local levels that are likely to occur if these are not appropriately tackled (Andrews-Speed et al., 2012).

Axes and variables considered. It considers the three nexus axes (water, energy and food) and adds up land and an additional one: minerals.

Actions needed. It identifies potential opportunities in taking action in several areas including resource efficiency, inclusion of new players, greener growth, institutional building, and engaged cooperation to address security conflicts.

International Institute for Sustainable Development (IISD) 2013

Purpose. It is an ecosystem management centred framework that aims to provide implementation guidance through collaboration, visioning and planning at various levels of decision making (Bizikova et al., 2013).

Axes and variables considered. It considers the three axes and builds an individual security cluster for each of them including utilization, access and availability aspects. These clusters are surrounded by concentric rings symbolizing natural and built systems that provide resources and influence resource access and supply (Bizikova et al., 2013). A final ring that encompasses all the previous ones represents the human and institutional elements of water, energy and food securities, including governance, markets, etc., as shown in Figure 2.4.

Action needed. Increased securities require from adequate and participatory planning. The study proposes a participatory planning process composed of four stages (1. Assessing the Water–Energy–Food Security System, 2. Envisioning Future Landscape Scenarios, 3. Investing in a Water–Energy–Food Secure Future,

4. Transforming the System) with an emphasis in assessment, monitoring and communication components.

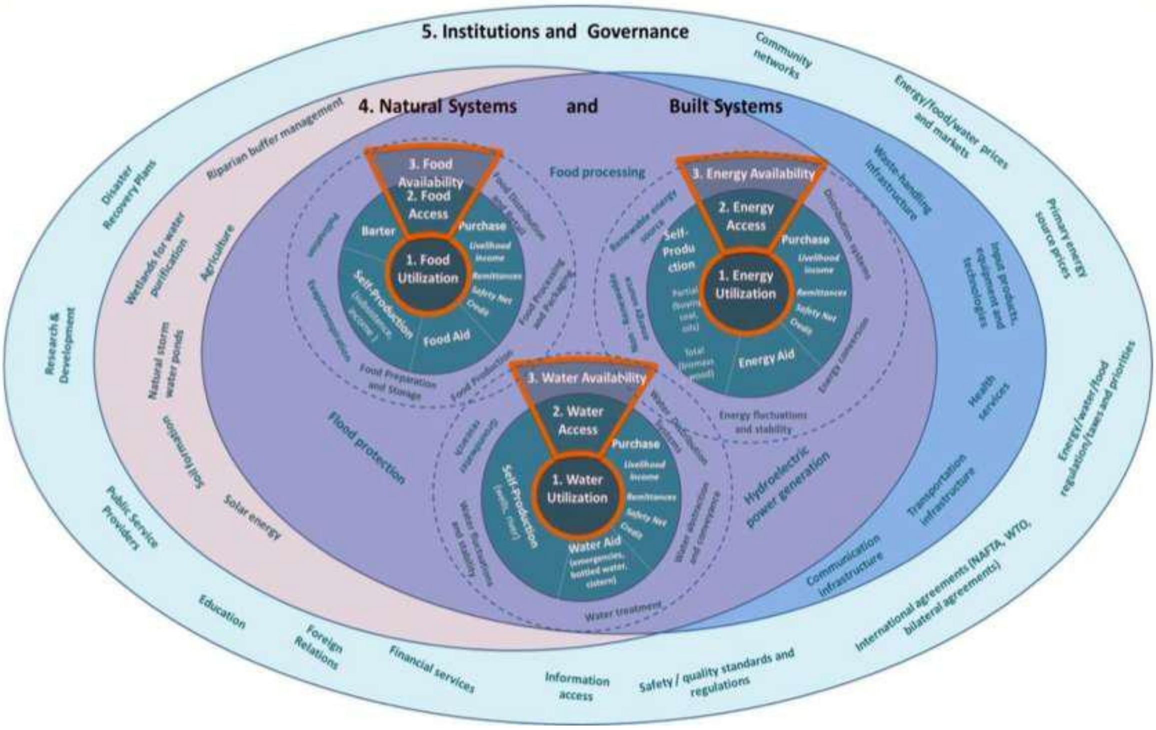


Fig. 2.4. International Institute for Sustainable Development framework. Source: Bizikova et al., 2013

Water for Energy and Food (W4EF) 2012-2015

Purpose. Provide the energy sector with a common terminology and assessment method to evaluate the relations between energy production and water (Lemoine & Bellet, 2015).

Axes and variables considered. This framework only includes the water and energy axes, looking at both cycles and the mutual requirements and impacts on one another, as shown in Figure 2.5. It aims to be comprehensive, practical, consistent, and applicable across all energy sectors and inclusive of all technologies.

Action needed. To allow an energy production site assess in a simple and accurate manner its interactions with its local water environment, a consensual methodology is required that includes the different ways of using water (including quantity and quality), interactions, calculation of several indicators, consideration of responsibilities, among others.

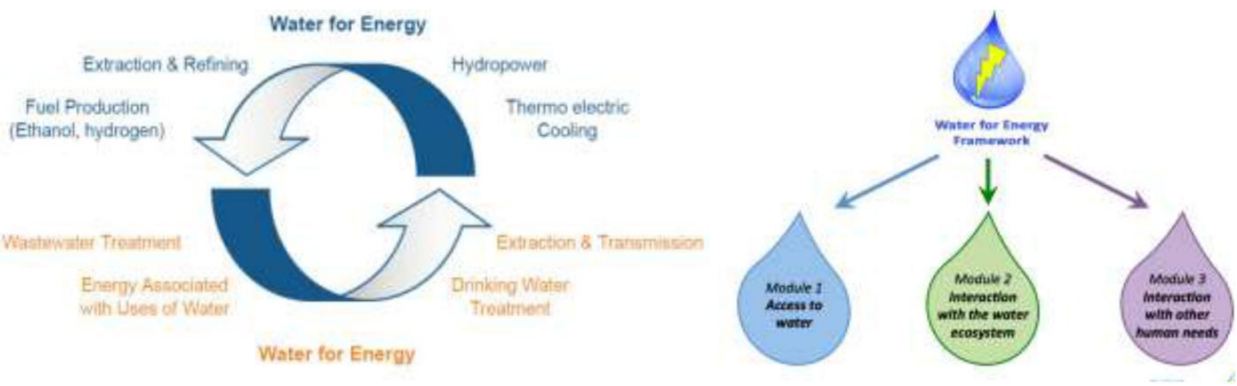


Fig. 2.5. Water for Energy and Food (W4EF) framework. Source: Bellet & Lemoine, 2014

World Business Council for Sustainable Development (WBCSD) 2013

Purpose. To provide co-optimized solutions for water, energy and food that also incorporate the inputs needed for those sectors along the value chain, like feed and fertilizers (WBCSD, 2013).

Axes and variables considered. The triangle water-energy-food, or food and fiber in this case, is turned into a square by the addition of climate change as a fourth interacting axe, as shown in Figure 2.6.

Action needed. It identifies ten areas where action is required: smart varieties, smart crop management, mixed farming systems, better blue water management, better green water management, efficient farm operations and mechanization, bridging the yield gap, efficient fertilizer production, making use of trade and reducing waste.

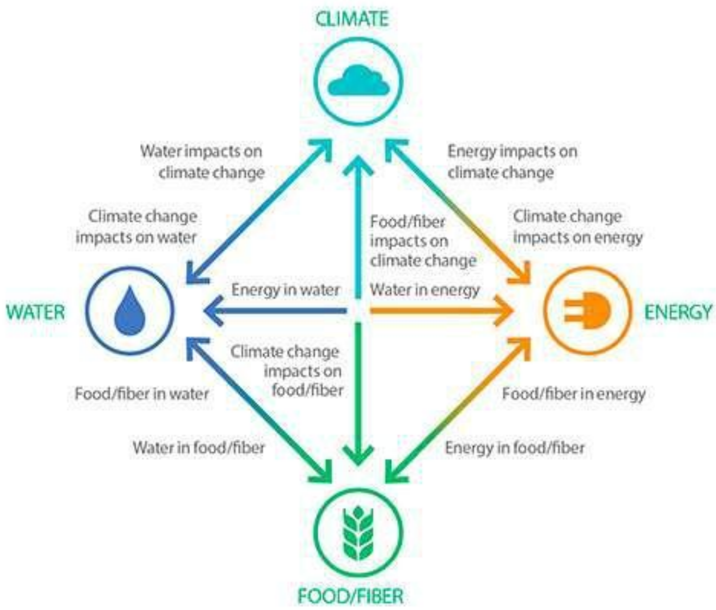


Fig. 2.6. World Business Council for Sustainable Development framework. Source: WBCSD, 2013

United Nations Environmental Program (UNEP) 2014

Purpose. This framework is aimed to show UNEP's view on the importance of ecosystems for the nexus and for realizing sustainable livelihoods and green growth (Boelee et al., 2014), as shown in Figure 2.7.

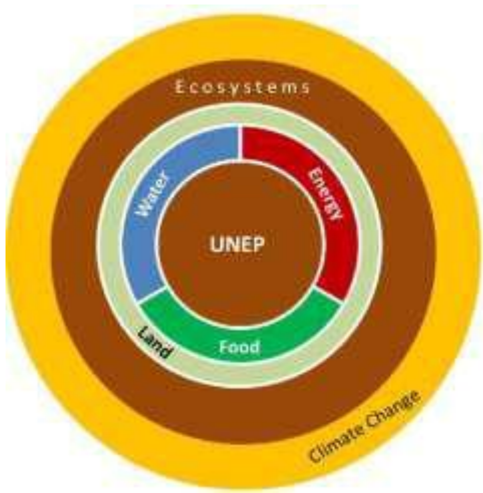


Fig. 2.7. United Nations Environmental Program framework. Source: Boelee et al., 2014

Axes and variables considered. It shows the water-energy-food nexus circle at the centre surrounded by a land dimension, and placing ecosystems both inside and around these four elements. All of them are also contained within a bigger climate change circle representing its influence as an external driver.

Action needed. It identifies the need for action in seeking synergies and integration of energy development, water resources management and rural development; promoting dialogue at international, local and stakeholders scale; and conducting innovative science to fill the knowledge gaps.

Food and Agriculture Organization (FAO) 2014

Purpose. It aims to build a framework to identify and assess the water and energy connections to food security as a support to FAO's mandate of achieving food security and eradicating hunger, reducing poverty, and sustainably managing and using natural resources and ecosystems (FAO, 2014a).

Axes and variables considered. It starts by characterizing a food security cluster with all the interacting variables. From this cluster it develops a complex dual framework with two clusters: a development goal cluster where the water, energy and food axes are included; and a resource base cluster that includes land, water and energy resources and the human capital involved in their use (capital, knowledge, labour). These clusters are connected by a stakeholder dialogue interphase and surrounded by a series of influencing external drivers, such as climate change, governance, population growth, markets, urbanization or technology and innovation, as shown in Figure 2.8.

Action needed. It identifies three areas where action is required: data and analysis, scenario development through quantitative (WEAP-LEAP or MuSIASEM) and qualitative tools and response options, complemented by a continuous process of stakeholder dialogues (FAO, 2014a).

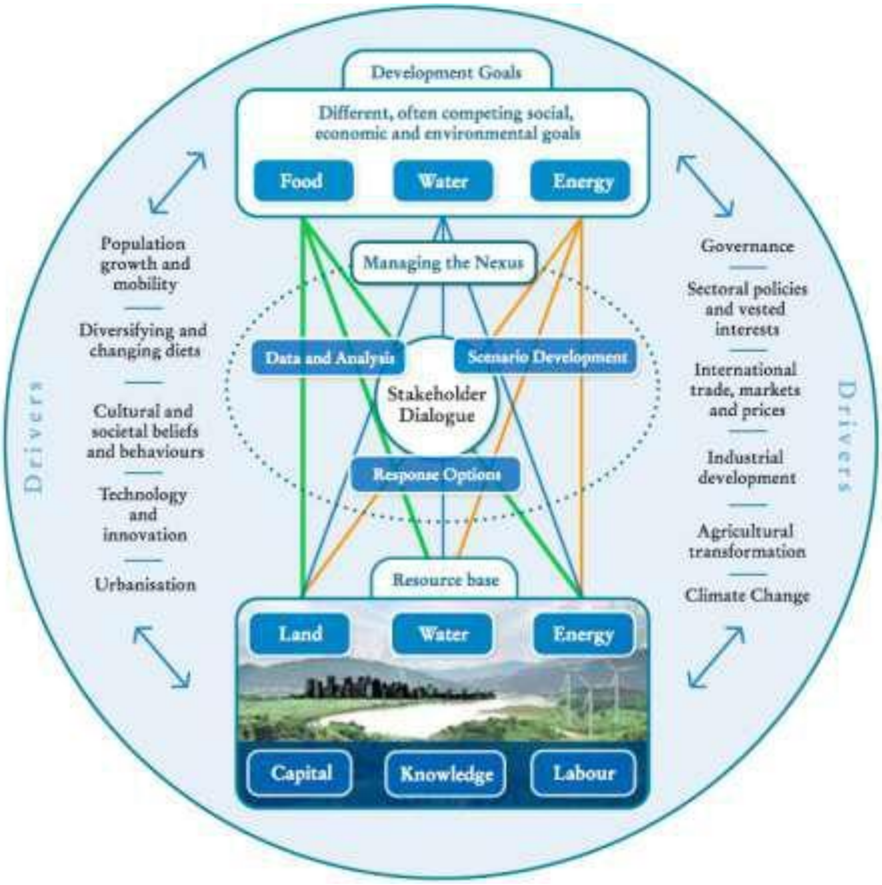


Fig. 2.8. Food and Agriculture Organization framework. Source: FAO, 2014a

Other related conceptualizations applied to the urban context are those of the German Development Cooperation (BMZ, 2013) and the Climate, Land, Energy and Water (CLEW) coalition (Segerstrom, 2014) formed by several international organizations and research institutes including FAO, IAEA, IIASA, IRENA, KTH, SEI, UNDESA, UNIDO and WBCSD.

Upon review of the frameworks presented, it is observed that most of the conceptualizations about the water-energy-food nexus (and possible additional axes) have their focus on three points: 1. the understanding of trade-offs between these three elements; 2. the assessment of the consequences that internal and external changes in each one can bring to the others; and 3. the stimulation of policy responses that can address positively the possible implications for water, food and energy security. This conceptual approach aimed at policy guidance and resource management improvement at the political and institutional scale will also be the one adopted for the purpose of this thesis. This aspect is further developed in chapter 4. However, it should be noted that a complete WEF nexus framework should not be restricted to the political and institutional levels, since resource management also is required at business and household levels. It should be framed and applied in order to build resilience at all scales, spanning from an enterprise business model or an industrial production process to the individual level (e.g. a livestock farmer).

2.1.3. Nexus vs. Integrated Water Resource Management (IWRM): what is the added value of the ‘nexus approach’?

The previous section has presented the different conceptualizations of the WEF nexus. It has also been highlighted that these approaches emerged with the aim to provide policy guidance towards the improvement of natural resources management. However, the existence of other approaches with the same or similar goals, like IWRM, has motivated a debate on whether all this nexus speech is old wine in a new bottle or it really contributes something new (Dupar & Oates, 2012; UNSGAB, 2014; Muller, 2014; Allouche et al., 2014; Benson et al., 2015). Indeed it is also under discussion whether the Nexus will or should be replacing previous approaches like IWRM, or it can be complementary. In other words, what is the added value of the nexus approach?

Some recent studies posing this same question have reflected on the conceptual basics of these two approaches, finding their similarities and differences, and drawing similar conclusions (UNSGAB, 2014; Muller, 2014; Allouche et al., 2014; FAO, 2014a; Benson et al., 2015). At the beginning of this thesis a comprehensive comparative analysis of the WEF Nexus and the IWRM paradigms was performed parallel to most of these studies, reaching some similar reflections and conclusions. This section aims to present this analysis and comment on the results and conclusions compared to the current literature. Since an introduction to the WEF nexus concept has already been provided in the previous section, the analysis will start with a description of the IWRM paradigm to later assess the two approaches based on a series of important aspects.

The IWRM approach was born as an answer to the call for ‘the application of integrated approaches to the development, management and use of water resources’ included in the Agenda 21 during the United Nations Conference on Environment and Development (UNCED) in 1992. The most acknowledged definition was given by the Global Water Partnership (GWP, 2000), which defined it as ‘a process that promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner, without compromising the sustainability of vital ecosystems and environment' (p.22). It is a water centred approach aimed at promoting the sustainable management of water resources, from an integrated and holistic perspective. As conceptualized by Jønch-Clausen & Fungl (2001), IWRM aims to account for all the elements, factors or variables that can have an influence on water resources, from both the natural systems sphere (physical resources, water quality, water pollution) and from the human system sphere (institutions, stakeholders, policies, legislation). This approach has its basis on the following essential pillars:

- Integration of all types of water resources, including surface and groundwater, blue and green water, fresh water and coastal water; and characterization through water accounting and water quality assessments.
- Integration of upstream-downstream interactions and related interests.
- Integration of all stakeholders and institutions across sectors (cross sectoral integration) and scales (at regional, national and international level).
- Assessment of the impacts on water quality and ecosystems, with special attention to ecosystem services.
- Consider economic aspects of water and link water policies to national security and trade policies, especially important in the case of transboundary waters.
- Integrating water resources planning with international cooperation and poverty alleviation.

Once the two paradigms have been presented, they will be systematically compared on the basis of a number of characteristics or indicators, including target, focus, approach, frame, goal, scale, aspects connecting to global scale, action pillars-tools and other fields of interconnection. The comparative analysis of different aspects of both paradigms is shown in table 2.3.

ASPECT	IWRM	WEF Nexus
Target	Water resources	Interactions between water, energy and food
Focus	Coordination and integration	Coordination
Approach	Holistic	Holistic
Frame	Scientific-political-practical Multidimensional: resource oriented, politically- institutionally oriented, socially oriented (stakeholders involvement) Cross-sectorality	Scientific-political-practical Multidimensional: resource oriented, politically- institutionally oriented, socially oriented (stakeholders involvement) Cross-sectorality
Goal (global terms)	Sustainable water resources management	Water, energy and food security and sustainable resources management
Scale	River basin, natural boundaries	Regional, local, national but subject to upper scale institutional arrangements
Aspects connecting to a global scale	Virtual water, transboundary basins	International energy markets (e.g. fossil fuels), international food markets
Action pillars-tools	Resource efficiency, resource accounting. Institutional coordination. Public-private cooperation	Technology, efficiency, policy coordination, water-energy-food trade-offs accounting. Public-private cooperation.
Other fields to which they are interconnected	Ecosystems-ecosystem services, economy, climate change, society (poverty alleviation), legislation, social media, land use planning.	Ecosystems-ecosystem services, economy, climate change, society (poverty alleviation), legislation, social media, land use planning.

Table 2.3. Analysis of the WEF Nexus and IWRM frameworks. Source: Own elaboration based on Scott et al. (2011) and Jønch-Clausen & Fungl (2001)

This itemization will enable to identify the synergies and differences between them, and serve as a basis to elucidate whether they are conflictive or complementary. However, it should be noted that without further comparative practical evidence on these two approaches, their extent and influence are difficult to judge (Benson et al., 2015). We can see from the table how the two paradigms share some important analogue characteristics:

- *The approach:* both are conceived from a systems thinking perspective with a holistic approach.
- *The goal:* both are aimed to endow a sustainable and optimized use and management of some resources that are of bare necessity for humans, and to ensure the security of access to and provision of these resources.
- *The frame:* both paradigms are framed from a scientific-political-practical point of view, integrating different dimensions: the natural systems sphere (resource oriented) and the human systems sphere (politically, socially and institutionally oriented). They also promote a multisectorial approach.
- *Action tools:* they identify some common tools as means to achieve resources security and sustainability, such as resource efficiency, resource accounting, political and institutional coordination or public-private cooperation.
- *Interactions with other fields:* both water resources and the WEF nexus have important interactions and trade-offs with other fields, such as natural ecosystems, economy, climate change, society, legislation or social media, that need to be taken into account.

However, some differences can also be observed:

- *Focus:* though both paradigms include aspects of integration and coordination to some extent, IWRM leans more upon integration of all the aspects and actors that can have an issue or affection on water resources. Meanwhile, the WEF nexus paradigm has its focus on the coordination of water, energy and food policies to optimize their management and avoid unintended cross-effects.
- *Scale:* the IWRM approach states that the most appropriate scale for the management of water resources is the river basin (Molden, 2007; WWAP, 2009), where all regional, upstream-downstream and transboundary (in the case of basins that run through more than one country) aspects should be accounted for. In the case of the WEF nexus paradigm, although some attempts some general estimates on the water requirements for the different energy technologies have been made (DOE, 2006; WEC, 2010; Schornagel et al., 2012; WEO, 2012), the wide range of values given for each technology show how these are very dependent on site specific factors, such as the type of cooling technology or the climatological conditions (Rodríguez et al., 2013). Therefore, more comprehensive studies have examined the nexus at local, regional, national or even basin scale (Newell et al., 2011; Opperman et al., 2011; Stillwell et al., 2011; Lawford et al., 2013). However, the adaptation of the legal framework to enable the implementation of effective measures needs to be done at national scale, or even at a higher level -the European Commission for instance-, in order to have enough competence and binding power to get a real response (Scott et al., 2011). Thus for the case of the WEF nexus approach all local, national and international scales have to be considered.
- *Target:* the main difference between the WEF nexus and the IWRM approach is the target they are aimed for. In the case of IWRM, water resources themselves are the main target: surface water and groundwater, fresh water and sea water, blue water and green water. The WEF Nexus has a broader

target. Other studies comparing the two frameworks have described the WEF Nexus target as all water, energy and food resources, arguing that it thus provides a less water-centred and more inclusive approach that can support more egalitarian dialogues across sectors (UNECE, 2015; FAO, 2014a; Muller, 2014). In this respect, this work aims to remark a small nuance that constitutes the core of the WEF Nexus concept, the reason why it emerged, and what makes the differences with other sectoral approaches. The target of the nexus is not the resources themselves - water, energy or food –, with management in hands of the corresponding management institutions, but the interconnections and interrelations between them, and to support and facilitate the coordination of institutions, policies and legislation regulating their management and use to avoid unintended and unexpected consequences.

These three differences, namely the scope, scale and target discussed above, and especially the last one on the interconnections, are the key point to discriminate whether these two approaches overlap or are complementary. At first they may seem to overlap as far as water resources are concerned. However, it is argued in this thesis that the WEF nexus approach is not meant specifically to provide a framework for water resources management, nor for energy or for food resources. It is meant to understand the interrelations and trade-offs between them and provide with solutions, tools and an adequate political framework that enables to optimize economic and social welfare, ensuring water, energy and food security while safeguarding environmental integrity. Hence, it is a complementary approach that should help coordinate the individual water, energy and food management policies by providing the knowledge to guide a process of revision and adjustment, led by the adoption of a broader looking perspective. This conclusions, with the added nuance of putting a higher emphasis on the interrelations aspects, is in line with those made by the main studies analysing the issue: UNSGAB, 2014; Muller, 2014; Allouch et al., 2014; FAO, 2014a; Benson et al., 2015; UNECE, 2015.

Based on this analysis, this thesis will propose a definition of the WEF nexus concept as 'the set of interconnections, trade-offs and interdependencies existing between water, energy and food as a result of their natural cycles and human use'. Therefore, a applying a Nexus approach would be aimed at and allow to understand and quantify the complexity of the interconnections and flows between the three resources and sectors, in order to promote informed and coordinated resource management. This conceptual framework is graphically represented in Figure 2.9.

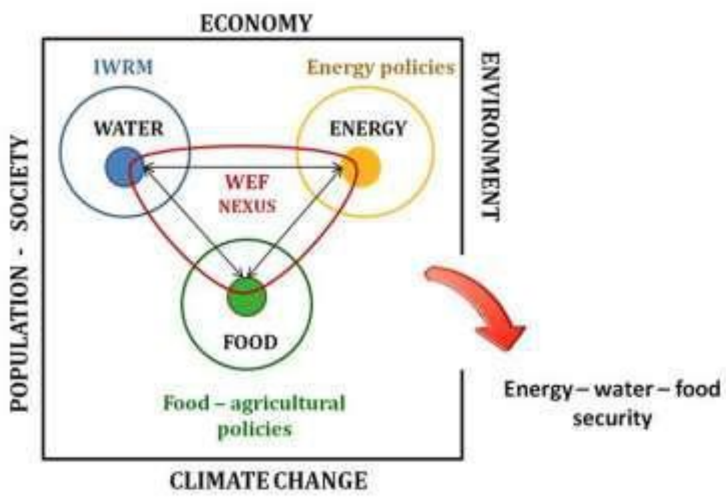


Fig. 2.9. WEF nexus framework. Own elaboration.

From a practical perspective, over the last decades the water sector has slowly started to consider the impacts from the other two sectors; especially from food, due to the evident connection through irrigation (Molden, 2007). This need to account for - and coordinate with - the water and food 'worlds' may be newer for the energy sector, where water and food had never been considered as core constraints or limiting factors before, beyond the wastewater quality standards the energy sector was obliged to comply with. The same happens within the food sector, where only in the last few years a growing concern has arisen on both the water and carbon footprints of food products, and the inefficiencies in food production chains. This has been fostered by the efforts of international organizations and symposia to increase awareness on these issues rather than by the practical application of an integrated approach (Lundqvist et al., 2008; FAO, 2011). Nonetheless, with energy and food market goods largely controlled and operated by the private sector, which has stronger economic power and interests than the public sector, these might have the capacity to quickly overtake the water sector.

Meanwhile, it should also be noted that water, energy and food are different resources with a different nature, properties, cycles and behaviours. An optimal management for each one also needs specialized and specific training. All the experience and cumulative knowledge gathered within the three sectors is of great value, and should not be neglected. In the particular case of water, where a big effort to promote an integrated approach to water resource management policies has been done, all the knowledge, experiences and successful examples achieved should be valued. It compiles and includes a series of detailed elements and aspects inherent to water resources (water quality, water ecosystems services, water cycle) and provides with a methodology and background knowledge to address water resources management that the WEF nexus approach has not necessarily included. Therefore, this reflection concludes that the WEF nexus approach cannot be understood in isolation, but as a complement to individual water, energy and food management approaches that will gradually lead to their coordination, harmonization and guidance by unravelling and highlighting interconnections among these three resources.

2.2. Present and future research trends on the water-energy-food nexus

2.2.1. Water-energy-food nexus and its axes

The water-energy-food nexus needs to be looked at as a whole integrated system, to fully understand and balance the interconnections among the three axes. However, these axes are not always perceived to have the same importance or have been studied to the same extent. After reviewing the existing literature, it was observed that the number of studies was considerably higher for the water-energy and the water-food axes than for the energy–food one. Meanwhile, within the studies considering the whole nexus, energy-food case studies were less frequent and mainly dealing with groundwater pumping, biofuels and land use issues. This observation raised the questions of whether the three axes were considered equally important and whether research in any of them needed to be particularly reinforced.

This question was posed to international experts as part of the European Commission's Project *Expert interviews and online survey* (see chapter 3 on methodology), and 58 answers out of 81 participants were obtained with the results shown in Figure 2.10.

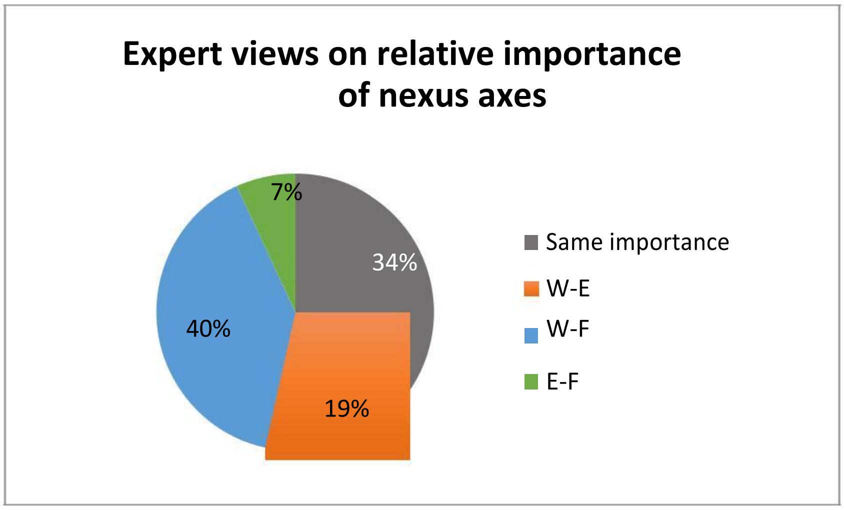


Fig. 2.10. Expert views on the relative importance of the Nexus axes. Own elaboration.

As shown in Figure 2.10, 34% of the experts argued that all the axes are equally important and should not be considered separately to avoid imbalances and sectorial thinking. The remaining 66% acknowledged the existence of differences to a certain extent. The highest percentage (40%) pointed at the water-food axe as both the one that has received further attention and has higher importance. Arguments stated that 'water is life', water is the essential element underpinning food and most of energy production and cannot be substituted, and both water and food constitute bare human necessities upon which human life and survival is primarily dependent. Third in importance, the water-energy axe was highlighted by 19% of the experts as the most important, or the one having higher impacts, but it was also considered the one where action capacity is higher since it has strong impacts in developed countries. The energy-food nexus was remarked by a minority (7%) and very linked to countries with high energy dependence, where food production dependence on energy may be a greater limitation than water availability. In general terms, the differential importance of the axes was considered variable upon the regional context and very politically influenced. Meanwhile, water was highlighted in a number of occasions as the core and most vulnerable resource, and a possible 'entry point' to the nexus, although the important baseline differences amongst the three sectors would make the operationalization of the nexus a very complex task.

From a personal perspective, none of the axes should be underestimated and all of them pose important challenges and opportunities that need to be further researched to provide a wide enough range of alternatives that permit the creation and trials of different combinations to adapt to the different contextual realities. For instance, energy-food trade-offs of a massive production of crops for biofuels in the Amazonic countries can have higher impacts on food security and rainforests integrity than water availability, which is abundant in the area (WWAP, 2014). Meanwhile, there are still important uncertainties within the energy-food axe that could drive high future impacts and need careful attention and research, such as possible long term effects of plant genetic engineering and the use of Genetically Modified Organisms (GMOs) on human health and the environment (i.e. insects and plagues naturally developing more resistance or possible effects on the human body). Therefore, both specific research on the three axes and the overall study of the whole system to identify emerging interconnections that may not be visible from a focused approach, are required to advance towards the development of inclusive management strategies that make communities resilient against future challenges in a context of higher uncertainty and variability.

The following section explores the main drivers and challenges influencing the nexus and the trends of technological research emerging within the nexus and its different axes.

2.2.2. General and sectoral trends: external and intrinsic nexus drivers

2.2.2.1. External drivers

As described in the previous section, the WEF nexus is rarely conceptualized as an isolated system formed by three axes and their interconnections, but as an open system that also interacts and is especially affected by other external drivers (Hoff, 2011; WEF, 2011; Bizikova et al., 2013; FAO, 2014a; Boele et al., 2014). This section presents the list of external drivers identified from literature review and expert interviews.

EXTERNAL DRIVERS AND INFLUENCES

GLOBAL DRIVERS: Climate change; population growth; urbanization; industralization; economic development; geopolitical conflicts; financial crises.

POLICY ASPECTS: WEF policy integration and coordination; water diplomacy and transboundary cooperation; implementation aspects and tools; collective and participative management; transparency, communication and capacity building; science-policy gap; foresight, adaptive and coherent planning; public-private cooperation; institutional reforms and cooperation; facilitating regulatory frameworks.

SOCIAL ASPECTS: Access to information; social awareness; social acceptance of new technologies; valuation of indigenous knowledge; integration and empowerment of women and youth; collective thinking and community resource governance; social media for empowerment; unemployment, low salaries and social unrest; inequalities and migrations.

ECONOMIC ASPECTS: Water, energy and food prices; financing challenges; cost of new technological developments; global markets; perverse subsidies and incentives.

BOX 1: Key external drivers and influences

Global drivers

Climate change. Climate change will strongly influence the nexus due to its multiple connections with energy, water and food. Some climate change related trends include the following:

- As a result of climate change, rainfall variability and water scarcity will be exacerbated in many regions causing water availability and supply constraints and challenging hydropower and rain fed agricultural production (WWAP, 2014; IPCC, 2015).
- Climate change will drive a rise on the frequency and magnitude of extreme events and natural disasters such as droughts, floods and hurricanes. This will pose rising threats to energy production, mostly dependent on water availability for cooling, and to food and biofuels production, with increased risks of crop failures. Natural disasters will also threat the integrity of energy and water infrastructure, where the generalized poor investment in maintenance and refurbishment increases their vulnerability in the mid-long term (Hoff, 2011; UN Water, 2014a).
- Climate change driven policies and strategies aimed to reduce green house gas emissions (GHG) can have negative externalities on water and food if these aspects are not considered in the selection of energy technologies. Technologies considered low carbon such as first generation biofuels, thermal power coupled to carbon capture and storage (CCS) systems or unconventional natural gas can have important impacts on water and food (WWAP, 2014; elite interviews).

Population growth. World population doubled from 2.5 billions to 5 billions between 1950 and 1990, rose up to 7 billions in 2010 and is expected to reach between 9 and 10 billions by 2050 (UN, 2014). This expected growth will drive a rise in water, energy and food demands and additional pressures on water, land and natural resources.

Urbanization. Currently more than half of the world's population lives in cities and by 2050 the urban population is expected to nearly double reaching 6.4 billion (WEF, 2014a). Most of the increase in urban areas and populations will take place in middle-income and lower-income countries, where food insecurity issues are more acute and the need to expand access to water and energy supply and infrastructure will be a considerable challenge (Hoff, 2011). Though urbanization will involve a concentration of demands and reduce supply distances, it will also enhance ecological disruptions, pollution, GHG emissions and vulnerability to environmental disasters (WEF, 2014a).

Industrialization. The trend towards higher industrialization that accompanies economic development is causing important pressures on natural resources, rising GHG emissions and increasing impacts on the environment due to the still deficient internalization of environmental externalities. Industrialization is spreading over emerging economies and reaching all sectors, including agriculture, where large mechanized plots are rapidly overriding small traditional farms in most parts of the world, with higher associated impacts on the environment (FAO, 2010).

Economic development and higher living standards. Rising economic development involves higher economic activity and industrialization – this is more need for productive inputs -, higher rents and purchasing power and thus higher living standards, demands and consumption (Hoff 2011). Higher life standard prospects in emerging economies are fostering the wish to emulate western living patterns, currently based on consumerist habits, diets highly based on processed and protein rich foods with high water and energy footprints, food waste and low consumer awareness (Lundqvist, 2008).

Geopolitical conflicts. Geopolitical conflicts have impacts on water, energy and food issues since, as a result of globalization, international markets and transboundary agreements, these are no longer contained within local, national or river basin boundaries and local problems can have implications worldwide (Hoff, 2011). Upstream-downstream conflicts, regional conflicts – the recent case of conflicts between Ukraine and Russia posing threats to natural gas imports to Western Europe is a good example – and international conflicts can threaten water, energy and food security, through blockages on food trade, transnational energy infrastructures or downstream water availability in transboundary river basins.

Financial crises. Financial crises have an influence on the WEF nexus since advances in water-energy-food and climate change policies and investments get blocked by the lack of funds and eclipsed by other 'more urgent' investment and political priorities. Meanwhile, financial crises have impacts on global markets, food and energy prices and the carbon market. This together with the reduced economic capacity of states, companies and households have negative effects on food and energy security, especially for the poorest, while fostering the 'quick and dirty' paths to promote growth at low cost, which usually involve high environmental and social externalities (USAID, 2008).

Key political aspects with influence on the WEF nexus

Water-energy-food policy integration and coordination. The lack of integration and coordination of water, energy and food policies is a driver for inefficient resource management, cross-efficiencies and intended consequences fostering competence and conflicts among users and the unsustainable use of natural resources. Integrated approaches and policy coordination are required for a complete understanding of the trade-offs, development of coordinated and synergic strategies and achievement of win-win solutions for all stakeholders and social levels (Hoff, 2011; WWAP, 2014; UN Water, 2014a).

Water diplomacy and transboundary cooperation. Water transboundary diplomacy and cooperation are key aspects of influence since water availability; timing and quality are critical conditions for downstream food and energy security in shared basins. Water retention for hydropower production, ecological disruption by thermal discharges impacting fisheries, water requirements for cooling and irrigation and human supply are only some of the trade-offs involved in upstream-downstream relations. Transboundary dialogues and management agreements are crucial to ensure water, energy and food security along the basin while accounting for the maintenance of ecological and ecosystem services integrity (Boele et al., 2014).

Collective and participative management. Participative governance and bottom up approaches are two of the pillars of integrated resource management. This has been especially advanced within the water sector with the application of the Integrated Water Resource Management approach, leading to an increasing level of inclusion and valuation of contributions from all stakeholders in resource management decision making.

Collective intelligence systems are a strong tool in this sense and further interaction among water, energy and food stakeholders can promote the emergence of win-win and innovative solutions (Hoff, 2011; Hagmann et al., 2002).

Transparency, communication and capacity building. Transparency and communication are essential requirements for participative governance, implication and awareness of civil society, and financial and resource accountability from governments. Knowledge transfer between countries on successful experiences, technologies and tools is very important to catalyse the diffusion and adoption of new technological innovations. Meanwhile, the allocation of funds for the creation of capacity building programs, practical training, knowledge sharing and transfer within and among cultures is highlighted as a must to achieve sustainable development and management goals, as well as a field where extensive work needs to be done (UNW-DPAC, 2015a).

Gap between scientists and policy makers. Science can provide knowledge and evidence based guidance to policy makers in their decisions. However, there is need for further communication bridges to improve the intensity, formats and means of information flow (more user-friendly language, more dialogue platforms, more applied and reality focused research, more effective and direct communication) (UNW-DPAC, 2015a).

Foresight, adaptive and coherent planning. In the current context of uncertainty and variability driven by climate change, the development of foresight exercises and long-term, multisectorial and flexible planning, which allows for continued adaptation to changing realities and possible disruptive events, is identified as one of the keys to achieve resilience and WEF resources security (UNW-DPAC, 2015a).

Implementation. Going from concept to action and finding methodologies and tools to catalyse implementation of a WEF nexus approach on the ground is an important step that is only starting. International and national initiatives, working groups and case studies are emerging all over the world to advance on applied knowledge and experiences, as shown by the multiple alliances and case studies presented at the 7th World Water Forum in Daegu, Korea (WWF7, 2015).

Public - private participation and cooperation. Private-public participation for resource service provision, shared funding of investments and creation of research coalitions is an increasing and necessary trend that will enable easing the public financial burdens, while joining forces to foster innovation and advance towards sustainable and resilient WEF resource management (Hoff, 2011; WWAP, 2014; UN Water, 2014a).

Institutional reforms and coordination. Institutional reforms and internal coordination are crucial for efficient WEF resource management, though they have been rarely included in WEF nexus frameworks and assessments (Villamayor et al., 2015). Institutions are particularly important as they structure the incentives that actors face when they make choices from among a set of alternatives, and much work is needed in the development of coordinated institutional paths to address nexus conflicts (Villamayor et al., 2015, Hoff, 2011).

Facilitating regulatory frameworks. Coordinated regulatory frameworks that prevent contradictory overlaps and create a facilitating environment for the implementation of integrated measures and the adoption of new technologies are also key for advancing the solution of nexus conflicts and achieving sustainability (UNW-DPAC, 2015a).

Key economic aspects with influence on the WEF nexus

Energy and fuel prices. The costs of oil and gas production, both to operate and enhance current capacity, have been strongly increasng in recent years, thus causing an increase in the price of electricity and fuels for transport (FAO, 2010). An exception can be found in the U.S. where gas prices have decreased thanks to unconventional gas production, causing an exceptional revolution (EPRS, 2014). In general, energy prices are expected to continue rising, posing a constraint to energy dependent water facilities and keeping food prices on the rise, although energy efficiency measures could help soften electricity bills in most sectors (IEA, 2014).

Water prices. Water prices are generally low, especially for agriculture but also for industrial and urban use, and do not reflect the cost of the water supply and treatment services. This leads to an undervaluation of the resource while making the provision of water services economically unsustainable, which usually derives in poor quality and lack of maintenance (UNW-DPAC, 2015b; WWAP, 2012). In the case of the European Union, the ‘cost recovery’ principle set by the Water Framework Directive is driving progressive steps towards a rise of water prices to reflect service cost.

Food prices. The global increase of demand for agricultural products for food, feed and non-feed uses like biofuel production has driven a trend of high price volatility and increments for food commodities. In high-income countries this has been partially palliated by higher incomes and subsidies for agricultural production, while in poor countries food remains a very important part of household budgets and food insecurity is more acute (FAO, 2010).

Finance. The need for financial resources to invest in water and energy infrastructure, refurbishment of existing one, application of new more efficient technologies and application of measures and strategies against climate change is huge. According to World Bank estimations a USD 300 billion investment is required only to achieve universal access to safe water and sanitation reach (WWAP, 2015).

Costs of new technological developments. High operation, production or input costs are a strong limitation to certain technological solutions like desalination, photovoltaic power or wastewater treatment. The reduction of these costs, in some cases highly dependent on energy costs, will be a key driver for the entrance and widespread of new technologies that help release resource availability pressures (IRENA, 2015; DOE, 2014).

Global markets. Trade globalization and international markets have made a substantial difference in the capacity to meet food, energy and even water demands at regional scale. However, it has also brought externalisation of resource extraction to other regions, usually emerging economies with abundant natural resources, and exposure of countries to higher volatility (Hoff, 2011). Food imports and exports have increased and will continue doing so, with rising price volatility strongly influenced by the price of energy (WBCSD, 2014). Meanwhile, virtual water flows constitute a vehicle to release water demand pressures in water scarce areas (Mekonnen & Hoekstra, 2011).

Perverse subsidies and incentives. The prices of water, energy and certain agricultural products are strongly affected by subsidies aimed to support industry and its competitiveness, but which distort the true economic relationship between these resources (WWAP, 2014). In the case of water and energy, these subsidies usually encourage higher consumption, a phenomenon known as the rebound effect (Dumont et al., 2013), and and which put more pressures on already scarce and costly resources (Komives et al., 2005). Water subsidies result in a price that does not reflect the cost of the service, thus preventing cost recovery from infrastructure investments and operation (UNW-DPAC, 2015b). Subsidies to certain agricultural crops to promote biofuels are causing important competition with food in regions like China (WWAP, 2014), while in Europe the Common Agricultural Policy (CAP) subsidy system is creating dependency of agricultural rents and a reduction of diversification (Salmoral, 2014).

Key social aspects with influence on the WEF nexus

Access to information and social awareness. Society being informed and aware of the threats of resource availability constraints and the need for a change towards more rational consumption patterns is essential to restrain the rise on resource demands. Awareness raising campaigns and initiatives, which create local consciousness and valuation of resources, civil education and societal value structures can play a pivotal role to reduce WEF nexus pressures. Meanwhile, access to information for civil society is still limited though efforts towards higher transparency and corporate stewardship are emerging, especially within the private sector (UNW-DPAC, 2015a).

Social acceptance of new technological alternatives. Social acceptance or rejection is a powerful factor that can condition the success or failure of a new technological development (Gupta et al., 2012). Social opposition against certain technologies that generate physical or psychological refusal (reuse water) or are perceived as unreliable, unproven or controversial technologies (Genetically Modified Organisms (GMOs) or hydraulic fracturing) pose the question of whether it is something temporary that will be overcome with time, or it will be a burden preventing these technologies to get implemented in certain regions or to have enough market demand.

Valuation of indigenous knowledge. Local knowledge is rooted in people's interaction with their environment, and hence has logical, experience based and usually cost efficient answers. Valuing and empowering local knowledge and capacities can provide in many cases cost efficient decentralized solutions that combine traditional knowledge with innovative insights, thus working efficiently and sustainably (UNW-DPAC, 2015a).

Integration and empowerment of women and youth. Women and youth constitute a strong workforce and can be a most disruptive driver: they can build a future or create a war (Bouman-Detener, personal communication). Making women and youth part of society, the development of their own society, and have them involved in societal, resource management and decision making structures is key to achieve sustainability. Women and youth can also be a critical driver of social behaviour change towards more sustainable consumption patterns, since women constitute the main household managers and youth will shape the behaviour patterns of the present and future generations (UNW-DPAC, 2015a).

Collective thinking and community resource governance. Initiatives of collective thinking and community resource governance are emerging in different areas. Examples can be found in groundwater user irrigation communities and use as well as management of decentralized water and energy systems in rural communities (UN Water, 2014a).

Social media as a vehicle for social participation and empowerment. Social media are giving civil society an opportunity to raise their voice and actively participate in local resource management (Luu, 2013).

Unemployment, low salaries and social unrest. Social unrest is a major risk for resource management and security, public service provision and business activity. High unemployment and low salaries can drive lower quality in business and public performance, while social unrest can cause costly delays to new projects and operations (IPIECA, 2015). Meanwhile, it can derive in criminal acts and social revolutions threatening water and energy infrastructures, food production and access to basic resources.

Inequalities and migrations. Inequalities (north-south, rural-urban) are a classic cause of demographic migration flows: from rural areas to cities, from low-income countries to higher-income countries, together with wars and geopolitical conflicts. However, new migration flows are being initiated driven by climate change and natural disasters, water stress and food insecurity, with impacts on regional demands and the emergence of new migration sink areas (van der Valk & Keenan, 2012).

2.2.2.2. Intrinsic drivers and research trends

WEF NEXUS

WEF NEXUS DRIVERS AND TRENDS
Data collection, processing and management: Data collection and management initiatives; qualitative tools; quantitative tools and models; risk assessment and multistrategy planning; piloting and monitoring; spatial tools; ICTs; auditing tools
Groundwater overexploitation and depletion: Measuring and monitoring systems and sensors; groundwater replenishment and restoration; renewable energy for water pumping
Increased resource demands and higher resource efficiency: Circular economy; water and energy metering; water productivity in agriculture; reduced food waste; water-energy conservation along the supply chain
Increasing water availability constraints: Research on alternative water resources: desalination, water reuse and recycling; water as by product; rain water harvesting
Sustainable Development Goals: Expansion and refurbishment of water and energy infrastructure
Food waste: Food waste reduction; resource efficiency along the supply chain; sustainable consumption

BOX 2: Key WEF Nexus drivers and trends

Data collection, processing and management

Data availability is one of the main nexus challenges, since data on surface and groundwater availability and quality, water-energy-food resource flows and footprints and related impacts on the environment are scarce and disperse. Research lines in this sense include the following:

- **Further data collection and management initiatives.** Real time and short term measurement and monitoring systems as well as tools for data management and computation are required to generate more precise and evidence based data (DOE, 2014).
- **Development of qualitative tools for knowledge generation and management of the nexus challenges.** Qualitative tools range from single estimates to probabilistic approaches, insights into potential system shocks and extremes and improved overall characterization of uncertainties. They also include participatory approaches, scenario thinking, expert panels, among others (DOE, 2014).
- **Quantitative tools and integrated models.** There is a need to develop robust integrated models including water, energy and food variables, as well as elements from life and social sciences. These models need to be validated with empirical data and go through multiple calibration-validation cycles to ensure their accuracy, and increasingly tend to include user friendly-GIS based interphases (DOE, 2014). Examples of integrated water-energy models are the WEAP/ LEAP (SEI, 2012) or MuSIASEM (FAO, 2013a).
- **Risk assessment and multistrategy planning.** Multistrategy planning based on projections of possible future scenarios and elaboration of alternative strategies are crucial to manage the risk of extreme events (Drought and Flood) and cope with climate change related uncertainty. They need to be flexible and adaptive, with periodic revisions and adaptations and fed by robust data measuring and monitoring systems (UNW-DPAC, 2015a).
- **Piloting, implementation and testing/monitoring.** Applied research with pilot projects is required to advance experiences and speed the entrance of new technologies into the market. The design of pilot projects is part of the strategy of Nexus working groups like the Sustainable Energy for All Nexus WG II (Enskat, 2015).

- **Accounting and analysis tools.** Tools for better accounting of water, energy and food resources and understanding of the systems are being increasingly developed and improved. The environmental footprints (carbon footprint, water footprint), Life Cycle Analysis, Risk Cycles and trend analysis are some of the most relevant.
- **Spatial tools, mapping and remote sensing.** Spatial tools, use of satellite information, maps and remote sensing are getting essential tools for land use planning and integrated resource management (DOE, 2014). Trends in research include continual refinement of Geographic Information Systems (GIS) with the ability for real-time monitoring of agricultural crops and water quality and quantity (Foster, 2010).
- **Information and Communication technologies.** Communication of data has to be facilitated through user-friendly interfaces to make the information process efficient and accessible. Information exchange platforms, stakeholder dialogues, online databases, social media, expert networks, platforms to gather expert knowledge from different stakeholders (connection science-policy making) can provide room for debate, knowledge and facilitating access to data for the broad public (DOE, 2014).
- **Auditing tools.** Auditing tools to certificate environmental performance are gaining importance. Some auditing and disclosure tools experimenting considerable expansion in the last decades include ISO norms and standards, water stewardship approaches to transparency on business water use and economics (Alliance for Water Stewardship, water stewardship indexes), disclosure platforms and initiatives (CDP, Frackfocus) or eco-labelling (UNW-DPAC, 2015a).

Groundwater overexploitation: a problem where water, energy and food converge

Groundwater holds 99% of the planet's accessible freshwater and provides water for human consumption and irrigation for one third of the population (FAO, 2015). Agriculture has strongly relied on groundwater in many regions, especially where surface water is scarce or variable, and its intensive development has caused around 20% of world aquifers to get overexploited (Mascarelli, 2012). In this context, there is a claim for legal, regulatory and institutional frameworks for groundwater that establish public guardianship and collective responsibility, permanent engagement of stakeholders and beneficial integration with other sectors, including other uses of the subsurface space and its resources (FAO, 2015).

Current trends of technological innovation in this line include the following:

- Development of measuring and monitoring systems and sensors to get better estimations and control of groundwater levels, quality and depletion rates (DOE, 2014; WWAP, 2014).
- Groundwater replenishment and restoration using treated or recycled water (DOE, 2014).
- Creation of Groundwater User Communities in overexploited aquifers to improve groundwater management and even revert the trend (Llamas & Custodio, 2003).

Circular economy: closing the resource cycle

Moving towards a circular economy is at the heart of the resource efficiency agenda established under the Europe 2020 Strategy for smart, sustainable and inclusive growth. Circular economy means re-using, repairing, refurbishing and recycling existing materials and products. What used to be regarded as 'waste' can be turned into a resource. All resources need to be managed more efficiently throughout their life cycle. Better eco-design, waste prevention and reuse and resource recovery from i.e. wastewater can bring net savings for EU businesses of up to EUR 600 billion, while also reducing total annual greenhouse gas emissions. Additional measures to increase resource productivity by 30% by 2030 could boost GDP by nearly 1%, while creating 2 million additional jobs (European Commission, 2015). Circular economy initiatives have already been started within the private sector, and are expected to increase in the coming years (Ellen Mc Arthur Foundation, 2013).

Food waste: the greatest source of water and energy losses

At a global scale, food waste accounts for one third of global food production causing important environmental and economic impacts (Lundqvist, 2008). Food waste and losses also involve the loss and waste of the water and energy used for its production, from growth, harvest and transportation to processing, packaging and distribution. Food loss takes places at different stages: in the field due to crop failures or deficient conservation during storage or transportation, during the industrial processing due to restrictive selection and chain inefficiencies, and at the distribution and consumer level due to non-unified quality regulations, misleading expiration date labels and poor awareness (Bagherzadeh et al., 2014). Reducing world food waste and loss by a half by 2050 would diminish by 22% the food production growth requirements to meet the global food demand (FAO, 2013a), and thus reduce demand pressures on water and energy.

WATER ←→ ENERGY

WATER ←→ ENERGY DRIVERS AND TRENDS

Energy thirst for water: Water accountings for energy; efficient cooling, water recycling and reuse practices; alternative injection fluids; low water footprint biofuels

Water thirst for energy: Energy accountings for the urban water cycle; low energy consumption devices; smart systems and technologies, energy production in WWTP[5]; green infrastructure; coupled renewables-desalination; nanotechnologies

Low carbon energies: Research on water trade-offs from hydraulic fracturing, first generation biofuels, carbon capture and storage (CCS), hydropower

Increasing water availability constraints: Research on alternative water resources: desalination, water reuse and recycling; water as by product; rain water harvesting

Water pollution: Water quality standards and monitoring; transparency platforms and disclosure; treatment of contaminants of emerging concern (CEC); reduction of diffuse pollution.

BOX 3: Key Water ←→ Energy drivers and trends

Increasing water and energy demands

Global energy demand is expected to rise by 37% by 2040 (IEA, 2014). Meanwhile, global water demand prospects forecast a 55% increase by 2050 (OECD, 2012). As a result, increasing efforts in technological research can be observed in the following areas:

- Development of water and energy use control and monitoring systems (DOE, 2014; ECN, 2014; UN Water, 2014a).

[5] WWTP: Waste Water Treatment Plants.

- Further development and refurbishment of energy and water infrastructure, including old thermal plants (i.e. in the U.S.), large and small hydropower and piping, conveyance and distribution systems (DOE, 2014; UNW-DPAC, 2015a).

Growing water scarcity and availability constraints

The number of regions suffering from water scarcity and rainfall variability is increasing all over the world, leading to water allocation, management and distribution conflicts and groundwater overexploitation (WWAP, 2012). As a result, increasing efforts in technological research can be observed in the following areas:

- Development of technologies to maximize water availability and productivity like rain water harvesting systems. The most remarkable technological lines include:
    - *Desalination* of saline waters is an option mainly constrained by the energy intensity, which will depend on the volume of the water being desalted, the quality (i.e., saltiness) of the source water supply and the technology used to desalt the water (Bennett et al., 2010). The selection of saline waters and type of desalination technologies are key aspects. Meanwhile, designing of less energy intensive technologies, upgrading of energy efficiency of existing ones and application of energy recovery devices are main research targets in this field (Water in the West, 2013; IRENA, 2015). Most important desalination technologies include forward osmosis, membrane distillation, dewvaporation, capacitive deionization, hybrid systems or nano enhanced membranes, vapor compression, multiple distillation, electrodyalisis, among others (DOE, 2014; Water in the West, 2013).
    - *Water reuse and recycling* through partial treatment of wastewater or separated conveyance of wastewater streams (grey and black waters) is a promising option, though studies on the added energy consumption by each method would be advisable to select the best alternative for each case (Water in the West, 2013). As a drawback, this method currently has low social acceptance in most places.
    - Processes that generate *water as by product* can pose important opportunities. Examples are the combustion of hydrogen, the methanation reaction or the Fischer-Tropsch process (ECN, 2014).
    - *Rain water harvesting* systems allow for decentralized collection of rainwater from rooftops, the land surface or rock catchments using simple techniques such as jars and pots as well as more complex techniques such as underground check dams (MAESTRO Database, UNEP-IETC, 2015). These solutions are very extended in Asia and Africa and can provide a decentralized complementary water supply.
- Groundwater injection for aquifer recovery. The injection of reuse water into overexploited or contaminated aquifers to improve water quality, stop sea water intrusion and restore water table levels is increasingly being practiced in the U.S. and other regions (DOE, 2014).

Growing energy thirst for water and consideration of water as serving resource

As global energy production rises, the amount of water used and consumed by the energy sector becomes higher. This poses competition for water resources at local scale with other users while increasing the vulnerability of the energy sector to water scarcity and water related disasters. Some of the main technological trends to help reduce energy dependence on water include the following:

- More accurate estimations of the water withdrawal and consumption flows for the different energy technologies and the energy mix at regional-local scale, since these can substantially vary depending on local variables, resource availability and accessibility and the composition of the mix (IRENA, 2015).
- Research and development on water efficient cooling systems with minimum energy requirements and yield reductions (DOE, 2014; WWAP, 2014; Rodríguez et al., 2013).
- Enhanced water recycling and reuse practices, with primary onsite water treatment when required. This is an especially upcoming trend within the oil and gas sector (DOE, 2014; ERM, 2014).
- Research on alternative injection fluids for oil and gas activities. Materials being researched include gels CO2, polymers, among others (DOE, 2014).
- Low water consumption crops for biofuel production, use of hydroponics crops or genetically modified organisms, and research on low water consumption biofuels like microalgae or wastes, which are at a very pilot level (WWAP, 2014).

Rising water thirst for energy

The urban water supply cycle is becoming increasingly energy intensive. Higher energy requirements from the water sector can become a limitation for water supply. Solutions to optimize water and energy use along the water supply system are being researched in the following lines:

- Further accounting studies on energy consumption for water conveyance (groundwater pumping, surface water diversion), transport and distribution (piping and pumping), treatment to drinking standards and treatment of wastewater streams (Water in the West, 2013).
- Study and comparison of energy intensity of different technological alternatives (types of pumps, types of desalination technologies, types of wastewater treatments) and research on the reduction of energy intensities (Water in the West, 2013).
- Smart conveyance and distribution system designs that allow energy recovery in down slopes, water jumps and 'in-conduit' hydroelectricity (Water in the West, 2013).
- Energy production and conservation in wastewater treatment plants: recovery of kinetic energy from wastewater flows and chemical energy from dissolved biomass, treatment sludge or wastes (Water in the West, 2013). Energy conservation measures such as load shifting, variable frequency drives, high-efficiency motors and pumps, equipment modifications and process optimization with and without Supervisory Control and Data Acquisition (SCADA) systems can reduce energy up requirements up to 30% (Klein et al., 2005).
- Use of green infrastructure, protected areas and extensive natural treatment methods (ponds, anaerobic treatment, constructed wetlands) to reduce the demands and energy intensity of wastewater treatment (White et al., 2006; Matamoros et al., 2007).
- Coupled renewable energy-desalination solutions: energy self-generation for desalination or water purification through coupled solar and wind energy devices (DOE, 2014; IRENA, 2015).
- Smart and IT technologies in buildings: technological innovations for buildings aimed to reduce resource use and waste generation include smart metering systems, decentralized energy production (green buildings, solar panels, geothermal heating) or smart controllable heating and cooling (independent heating, heat exchange pipelines), among others (Vattano, 2014; Hoff, 2011).

- Application of nanotechnologies to improve water purification: nanotechnology could provide inexpensive decentralized water purification, enabling the detection of contaminants at molecular level and more effective filtration systems (GIFS, 2015).

Increasing water pollution with energy trade-offs

Water pollution from energy related activities such as oil & gas production, first generation biofuels production or hydropower remains a crucial problem, threatening the achievement of the WFD quality objectives for European waters. Related to this, several trends can be observed.

- Inclusion of more stringent water quality standards, monitoring and objectives in river basin planning as a result of the WFD. This is complemented by the application of sanctions and fines (EEA, 2012).
- Transparency platforms for open public access to information (i.e. frackfocus) (ERM, 2014; DOE, 2014).
- Voluntary and mandatory disclosure initiatives for use of chemicals and potential pollutants in the oil and gas sector to increase social acceptance (EPA, 2012).
- Research on treatment technologies for Contaminants of Emerging Concern (CEC) such as pharmaceuticals, hormones and other chemicals present in wastewater, as well as on the additional energy costs (Water in the West, 2013).

Planning towards a low carbon economy with little consideration of water externalities

There are four technologies considered ‘low carbon’ that can entail considerable water externalities when largely deployed: first generation biofuels, carbon capture and storage technologies, hydropower and hydraulic fracturing.

- *First generation biofuels:* crop based biofuels require high quantities of water and land to grow the crops, thus creating competition with food crops or other water uses, especially in arid regions. Meanwhile, extensive use of chemical fertilizers and pesticides for biofuel crops production are causing serious water quality degradation problems. Illustrative examples can be found in China and India (WWAP, 2014). In certain regions like Brazil compatible and sustainable solutions are being explored, i.e. the development of agro-environmental certification schemes to encourage good environmental and social practices in biofuel production or the use of sugar cane (a non staple food) instead of maize or soya beans (FAO, 2013b). The sustainability of future bioenergy options should be evaluated on the basis of their sustainability from the standpoint of water use efficiency, impact on soil nutrient cycling, effect on crop rotation, and overall environmental benefits with respect to improved energy use efficiency and reduced GHG emissions, nutrient runoff, pesticide runoff and land-use impacts)(FAO, 2013b; IEA, 2010).
- *Carbon Capture and Storage (CCS):* CO2 capture processes are conceived as a solution to reduce emissions from thermal power processes. The level of maturity of the technology varies depending on the type of process, but all of them have a common feature: they cause an up to 50% increase in water requirements per unit of energy produced compared to single thermal power plants, while also reducing plant efficiencies (DOE, 2014). Research is being conducted to overcome these limitations, by i.e. exploring partial capture to reduce negative effects on plant efficiency, or treatment and reuse of wastewater to reduce water intensity (IEA, 2013). The International Energy Agency predicts that CCS will be present in 4% of total installed capacity by 2040 (IEA, 2013).

- *Hydropower:* large hydropower projects associated to big dams and reservoirs can provide multiple services (electricity generation, water storage, flood regulation, spaces for recreation), but also entail a series of social and environmental impacts, including impacts on river dynamics, water quality and disturbed connectivity of aquatic ecosystems. Individual small scale hydropower projects have similar impacts than large scale ones though in a much smaller proportion due to their smaller size; however, when widely deployed along a river, the cumulative impacts can reach or even outweigh those of a single large project with equivalent production capacity. Several studies are pointing out the need for a careful evaluation and planning of potential hydropower developments to avoid serious damages to the river and related ecosystems (Abbasi & Abbasi, 2011; IEA, 2012; Bakken et al., 2014).
- *Non conventional natural gas production through hydraulic fracturing:* The massive deployment of hydraulic fracturing projects for shale gas production in the U.S. has led to a reduction in the country's GHG, mainly due to the shift from coal fired to gas fired thermal power plants (Vihma, 2013). However, the exponential expansion of shale gas projects have also brought about constraints to water supply in certain regions – i.e. Texas, Oklahoma and California during the recent droughts – and certain cases of water quality contamination mainly caused by malpractice or insufficient protection (Puls, 2014). Global demand for natural gas is expected to increase by more than half by 2035, with unconventional gas accounting for 60% of global supply growth (IEA, 2011b). However, there is uncertainty over the potential development of an upscale shale gas deployment in Europe due to concerns over water management challenges and potential environmental risks, together with social opposition and crossed interests with national energy strategies. Other regions such as Mexico, Argentina, China and Australia, and more recently Colombia, Russia and Algeria, are also advancing towards active shale gas exploration and production (EIA, 2015).

  The use of hydraulic fracturing techniques to produce non conventional gas from shale has several water trade-offs that can pose considerable risks when improperly managed. Main water related risks from hydraulic fracturing come from the need of relatively high upfront water requirements to stimulate the wells, surface transportation and storage of fracturing fluids and storage and management of produced waters. Research and innovation trends to reduce these risks include research on non-water based fracturing fluids, use of more robust casing and cementing for the wells, water reuse and recycling and research on cost-effective onsite treatment technologies (EPA, 2012), as well as public disclosure to fight public opposition. Meanwhile, the elaboration and dissemination of good management practice guidelines, the introduction of more stringent regulations and controls, the definition of sampling and monitoring protocols to control potential impacts on water quality, or the voluntary/mandatory disclosure of chemicals, volumes and composition of water inputs and outputs are some legal initiatives taking place at the state level in the U.S. to regulate the activity (GWPC, 2014).

Promotion of low water consumption renewables

Photovoltaic (PV) and wind are being increasingly recognized as having great potential as low carbon-low water consuming energies (IRENA, 2015). However, further research to reduce their costs and overcome the intermittency problem through i.e. coupling them to other processes is required and should be potentiated to achieve market competence and widespread adoption (EWEA, 2014; ECN, 2014).

The Sustainable Development Goals: the path towards global access to water and electricity

Today 2.5 billion people still lack access to improved sanitation and 748 millions have no access to an improved source of drinking water (UNICEF and WHO, 2014), while 1.3 billions lack access to electricity (WEO, 2014). The Sustainable Development Goals (SDGs) proposed for the SDGs Post 2015 Agenda set the goal to achieve universal access to drinking water, sanitation and electricity by 2030 (UNW-DPAC, 2015a). To achieve these goals, decentralized water and energy alternatives will be key opportunities for rural and remote areas with access difficulties, including single small scale hydropower, solar devices for water pumping and depuration, traditional systems (UNW-DPAC, 2015a; IRENA, 2015).

Awareness on water-energy problematic as a driver for change

Rising awareness on the vulnerability of businesses to water and energy availability, their impact on production costs and the benefits of water and energy use efficiency and control are driving a number of initiatives and efforts in this line within the business sector.

- Water and carbon footprint and LCA frameworks as tools for efficient resource accounting (DOE, 2014; UNW-DPAC, 2015a).
- Voluntary water and energy corporative stewardship approaches are being increasingly adopted by the business sector, motivated by the recognition of their vulnerability to and dependence upon the internal and external management of these resources at sub basin or basin scale (UNW-DPAC, 2015a).
- Ecolabelling, carbon footprint certification and corporate stewardship used as advertisement tools to reach consumers also contribute to increase public information and awareness on the importance of these resources.

WATER ←→ FOOD

WATER ←→ FOOD DRIVERS AND TRENDS
Food thirst for water: Saline agriculture; resistant crops; efficient irrigation; water conservation; hydroponics and aquaponics; virtual water trade
Higher living standards and changing diets: Awareness raising; eco-labelling; product certification
Technological innovations: Biotechnology; genetic engineering; artificial foods; nanotechnologies; remote sensing; urban agriculture
Water pollution: reduction of diffuse pollution.

BOX 4: Key Water ←→ Food drivers and trends

Rising food and water demands

Global demand for food is expected to increase in line with world population. By 2050, a 60% increase in food production may be needed to meet global food demand as compared to 2007 levels, requiring a boost in productivity to limit the occupation of additional cultivated land to some 70 million ha (Alexandratos & Bruinsma, 2012). Meanwhile, water withdrawals for agriculture, which currently account for around 70% of global water withdrawals, are expected to increase to a lesser extent thanks to productivity improvements, with a 5% rise by 2050 (Alexandratos & Bruinsma, 2012). These prospects are driving some trends of technological innovation:

- Rising productivity of agriculture: important research is being conducted on ways to rise productivity of agriculture, which would drive particularly critical improvements in areas with low productivity thresholds like Africa (Hoff, 2011; FAO, 2012). Research lines include yield improvements in rain fed agriculture, use of supplementary irrigation, deficit irrigation, irrigation scheduling, and intensive agriculture, among others.

Higher living standards and changing diets vs sustainable consumption

Progressive economic growth and spending power in emerging economies is driving a shift towards more protein rich diets and rising demands for high water footprint foods (beef, high water footprint vegetables and fruits, industrial elaborated products). A clear example is the case of China (Lundqvist, 2008).

A countertrend can be found in movements of awareness raising on sustainable, healthy and balanced diets, product certification and eco-labeling, selective consumption of sustainable products or currents towards vegetarianism (Lundqvist, 2008).

Food thirst for water in a context of increasing water scarcity and variability

Increasing water requirements for food production will pose a constraint to water stressed areas, especially in the context of increasing water scarcity and rainfall variability due to climate change. More frequent episodes of heavy rains and floods or short-term and long-term droughts will strongly compromise the sustainability and reliability of agricultural production, and thus of food supply (WWAP, 2012). Some consequential and counteracting trends of technological research in this field include the following:

- Use of non-conventional water sources for irrigation: treated wastewater and grey water reuse for irrigation is becoming an upcoming trend, though also encountering considerable social acceptance barriers. Reuse of treated industrial water or even oil and gas produced water is also being considered, though in this case social opposition may result in absolute unworkability (DOE, 2014).
- Saline agriculture: use of saline water for agriculture, by shifting to salt-tolerant crops, and for aquaculture is expected to increase. Some techniques used to develop salt-tolerant crops include selection, hybridization, back crossing, tissue culture and genetic engineering (Lundqdvist, 2008).
- Development of resistant crops: the creation of seeds and crops that are resistant to the lack of water, insect plagues, higher temperatures and rainfall variability is being investigated using natural breeding and genetic engineering techniques (FAO, 2009).

Agriculture driven water pollution

Diffuse pollution from agriculture is the most difficult to address and mitigate. Trends to reduce diffuse pollution include the expansion of ecologic agriculture, minimum and localized input application (precision agriculture) or sustainable tillage and management practices (EEA, 2012).

Resource efficiency along the food supply chain and life cycle

Increasing trends to reduce water requirements and dependence from food production are driving an array of innovative solutions.

- Hydroponics and aquaponics: development of crops and fish that can grow with very limited water (FAO, 2014b).

- Water efficiency: increased water efficiency along the lifecycle of the food production and supply chain is being promoted. Good water management, water reuse, and water evaporation and loss reduction along the production chain are being applied at the industrial and manufacturing levels (DELOITTE, 2013).
- Efficient irrigation technologies and practices: at the field level, some trends to maximize water productivity and reduce evaporation losses include the application of high efficiency irrigation systems (drip, sparkling), deficit irrigation practices, use of GIS and remote sensing to monitor productivity, precision agriculture (with minimum water and fertilizers inputs), application of cellular and wireless communication technologies for irrigation systems, authomatization and control and green water management techniques (Molden, 2007).
- Nutrient recovery from waste water: the recovery of nitrogen, phosphorus and other nutrients from waste water, as well as the use of treatment sludge and solid waste as fertilizers, are some of the trends towards a circular closed-cycle economy (WERF, 2011; Hoff, 2011).

New technological developments

Particularly active research on technological development is being conducted in the following lines:

- Biotechnology: The main biotechnology applications in agriculture encompass marker assisted selection, genetic modification, propagation, therapeutics and diagnostics. In the livestock field, important biotech applications are breeding, propagation and animal health (OECD, 2009).
- Genetic engineering: genetic modification programs are focused on four main traits: herbicide tolerance, pest resistance, stress tolerance, and product quality, with the first two being dominant (European Commission, 2011).
- Artificial food and new foods (algae): mass artificial production of meat and proteins from stem cells in cultures or from genetically modified organisms with lower input requirements (water, land, grains) is being researched, though it is not a mature and socially accepted option yet. Other alternative protein sources already entering the market are meat replacements manufactured from plant proteins and mycoproteins and algae (Bonny et al., 2015).
- Nanotechnology: Nanotechnologies are applied in the food industry for several purposes: functional food packaging, taste improvements, enhancing the bioavailability of certain ingredients, reduction of certain nutrients (like salt and sugar) and microbial activity slow down (European Commission, 2011).
- Remote sensing, control systems and real time data for irrigation: relevant tools include automatized irrigation systems and the use of remote sensing technologies for irrigation scheduling, water metering and efficient application, as well as probabilistic models of water use and access to surface irrigation water. Drawbacks of these technologies include important upfront investments and considerable energy consumptions during the use stage (Foster, 2010).
- Urban agriculture: the creation of urban and suburban farms is a relatively spread trend in developing countries and is extending to developed countries like the U.S. as an alternative to increase food security of urban low income households (FAO-World Bank, 2008).

FOOD ←→ ENERGY

FOOD ←→ ENERGY DRIVERS AND TRENDS
Food thirst for energy: Smart tariffs; net metering; food preservation systems; energy self-generation.
Energy thirst for crops and food-biofuel competition: Advance in second generation biofuels.
Alternative efficient solutions: Integrated food-energy systems; aeroponics; energy recovery from biogas and food/agro wastes; coupled renewables and energy self-production in agriculture; Decentralized onsite renewable energy systems in food supply chains

BOX 5: Key Food ←→ Energy drivers and trends

Rising food and energy demands

Food and energy demands are expected to increase by 60% and 40% respectively by 2050. Currently the food sector accounts for 30% of global energy use and 22% of greenhouse gas emissions (UNESCO, 2015) through energy use, land use change, methane emissions from livestock and rice cultivation, and nitrous oxide emissions from fertilized soils. Meanwhile, an increasing part of soy, maize and sugar beet crops are being destined to biofuel production, thus posing a competition for land and other resources with food production.

Growing food thirst for energy

Currently the food sector accounts for 30% of global energy use (UNESCO, 2015). The increasing technification of agriculture is driving a rise on the energy demand of the sector, and consequently of the production costs. High amounts of energy are required for irrigation water pumping and transportation, food processing and distribution, as well as for the production of fertilizers and other chemical inputs, with prices strongly influenced by energy costs (FAO, 2012). Trends and technological research lines to face these aspects include the following:

- Smart tariffs: operate during the low fare hours when the demands for electricity are lower and the prices drop, e.g. during the night (Owen & Ward, 2010).
- Net metering: The possibility of selling the surplus electricity produced by decentralized renewables coupled to irrigation by feeding it into the grid has strong potential for farmers to get a quicker return of investment and additional income source. An example of a program facilitating this option can be found in Missouri (U.S.), where the Department of Natural Resources enacted a legislation requiring all electric utilities to offer net metering to customers with systems up to 100 kW (NAACP, 2014).
- Alternative ways of food preservation, such as food drying using low-temperature thermal sources can considerably reduce energy use for food conservation and food loss (IRENA, 2015).

Energy thirst for food crops

The promotion of biofuels as a low carbon energy solution to reduce the carbon footprint of transport is driving increasing demands for certain food crops (mainly sugar beet, maize, soy and wheat) and energy crops (jatropha and woody trees) for biofuel production (IEA, 2011a). This is posing competition with food production for land and water, while causing food price instability. On the other hand, crop fields are considered carbon sinks that help reduce the carbon footprint of energy. To reduce this competition, research on alternative technologies is being conducted:

- Second generation biofuels: emerging feedstock alternatives to food crops include woody crops, by-products from agriculture and forestry, organic waste or lignocellulosic materials (2nd generation biofuels); micro algae and micro bacteria (3rd generation biofuels) and engineered plants with special characteristics and low input requirements (4th generation biofuels). Within advanced biofuels, certain options like short-rotation coppice wood (poplar and willow) or energy crops (wheat straw, miscanthus, jatropha), although not directly competing with food products, still pose a competition for land, water and agricultural inputs with food production, albeit having the advantage to recycle nutrients and work as carbon sinks (FAO, 2013b). Other advanced techniques like the use of algae, urban waste, recycled oils or anaerobic production of gas biofuels (e.g. in wastewater treatment plants), have no added water requirements – i.e. algae can be grown in wastewater or seawater -, save space and help close the materials cycle (FAO, 2013b). The technologies to process these types of feedstock are still in a demonstration stage and have high costs. However, IEA estimates that by 2050 90% of biofuel based GHG reductions could come from advanced biofuels (IEA-ETSAP & IRENA, 2013).

Optimal resource efficiency

There is a trend towards sustainable food production systems that minimize the input requirements and maximize the quantity and productivity of the outputs, with particular development in the following areas:

- Development of aeroponics: aeroponics are plants that can grow considerable root systems without soil and far less water than what is traditionally considered necessary for plant growth. It essentially uses an air/mist system to rapidly grow plant crops (Foster, 2010). The can pose a great opportunity as low input biofuel source.
- Energy recovery from biogas and food/agro-waste in farms or biomass plants (IRENA, 2015).
- Integrated food-energy systems applying practices like inter-cropping can make the use of bioenergy sustainable and positive to rural development and environmental conservation, while avoiding perverse competencies (IRENA, 2015).

New energy solutions for irrigation

New technologies, mechanization and water availability constraints are turning irrigation into an important energy consumer for which energy availability and cost constitute a great limitation. Research on solutions in this field include the following areas:

- Coupled renewables and energy self-production: Decentralized energy production for agriculture by renewable energy systems (small scale hydropower, photovoltaic solar and wind devices) coupled to irrigation and water pumping are promising options (IRENA, 2015).
- Decentralized onsite renewable energy systems in food supply chains: On-site renewable energy resources can substitute fossil fuels for the provision of heat, electricity or transportation services within the agri-food sector. Anaerobic digesters that can process agricultural residues or animal waste are a good example (IRENA, 2015).

CHAPTER 3

AN EXPERT OUTLOOK ON WATER SECURITY, WATER FOR ENERGY AND FOOD SECURITY TRENDS TO 2030-2050

Chapter 3. An expert outlook on water security, water for energy and food security trends to 2030-2050

3.1. Introduction

As explained earlier, global factors like population and economic growth and climate change are driving rising demands and pressures on water and energy resources, and thus rising concerns for future water and energy security (WEF, 2014b).

Within the energy sector, water has started to be seen no longer as a mere input material that can be easily obtained at a cheap price, but rather as an increasingly scarce and strategic resource with variable operational costs. This cost variability, caused by e.g. an uncertain security of supply, is often dependent upon climatic variables and increasingly subject to competition with other users that may have higher priority of access during drought periods. Some of the most critical water related uncertainties and knowledge limitations within this sector are related to the variability and vulnerability of water resources. Despite the increasing efforts in accounting and different initiatives (WEO, 2012; ADB, 2011), estimates of present water demands and availability by region and at a global scale have higher variability than energy estimates, as accurate assessments and monitoring of water reserves are more complex and require specific technologies. Meanwhile, the fact that water is often not paid for – since the largest consumption comes from agriculture – and management is usually carried out by the public sector, has usually resulted in fewer incentives for accurate estimates. This is compared to an economic good like energy, mainly operated by private owned companies – even if often under monopolist regimes – and with variable prices usually complemented by substantial taxes (WWAP, 2014). Therefore, there is a special interest by the energy sector to introduce water aspects within energy strategic planning, to better understand potential future water related risks.

This chapter presents the results of a study leaded by the Technology Centre of the Spanish energy company Repsol in order to reduce uncertainty on some of the most important trends and variables affecting water security and the future development of energy technologies, through the outlook of water related Spanish experts. A summarized version of this chapter has been accepted for publication in Water Policy journal (see annex 1). The chapter is structured as follows: first a section describing the Delphi methodology and process. Second a section presenting the list of uncertainties and questions, followed by a brief introduction to the context of the question, and a quantitative and qualitative analysis of the experts' answers. Third a section analysing the performance of the Delphi study, including statistics about experts' participation and level of expertise. The chapter ends with a discussion of the results in view of other water-energy reports, and a set of conclusions and implications raised for water and energy policy decision making.

3.2. Delphi study methodology and process

The Delphi method (Dalkey *et al*., 1963) is a well-known social research technique aimed at obtaining a reliable opinion from a set of experts, as described in sectiom 1.4.2.4 on the methodology.

Based on the precedents and given the objectives and the conditions of long-term forecast and high uncertainty of the present study, the Delphi methodology was the best option.

The Delphi exercise was undertaken thanks to the collaboration of a selection of reputed Spanish experts mainly coming from the water sphere but with experience also in the water-energy-food aspects. The study was structured in the following steps:

1. Literature review of selected publications for a first selection of variables and future prospects.
2. Initial design of the Delphi questionnaire.
3. Pre-selection of experts. A selection of 40 Spanish experts was made based on the following criteria: a) extended academic and/or professional background in the water or energy field and specific contact with water-energy-agriculture interconnections and crossed-issues; b) active participation in events and conferences on the topic and c) representation of different stakeholders from both the private and the public sector.
4. Semi structured 'expert' interviews. Five experts with high level of knowledge – referred to as 'elite experts' during the process, were selected for a 90-minute interview with the aim to contrast and complete the variables, trends and data gathered in phase 1, and test the clarity and appropriateness of the first Delphi questionnaire draft.
5. Pilot Delphi. Revision and adaptation of the questionnaire, and pilot testing to control clarity and duration of the questionnaires.
6. Launch of the Heredera Delphi project in March 2013 at the Technology Centre of Repsol. Elite experts were invited to a workshop where the Water Delphi and the other nine Repsol Delphi studies were presented. A work session with the project leading scientific teams was conducted to discuss possible disruptive events and important interrelations among the represented driving forces.
7. First Delphi Round. The questionnaire containing 19 closed questions and 7 open questions was sent to the 40 pre-selected experts, where they were asked to grade their level of knowledge on a scale from 1 to 4 (Dalkey *et al*., 1970), to give a quantitative estimation for the statement to 2030 and 2050 time horizons, and to provide any additional comments or qualitative information they might consider of interest. Sixteen experts sent their answers back, composing the final list of participants. This list is included in Appendix 1, showing the final cast of experts, including their institutional profile and their role in the study (Elite experts, Experts taking the Delphi survey, or both).
8. Second Delphi round. Experts were sent a second personalized questionnaire including the first round questions, answers given by the expert, indicators of average trend and dispersion on the answers from the experts (median, quartiles and standard deviation), and a synthesis of comments and qualitative information provided by experts.
9. Analysis of results and elaboration of reports.

The scheme with the methodological steps is presented in Figure 3.1.

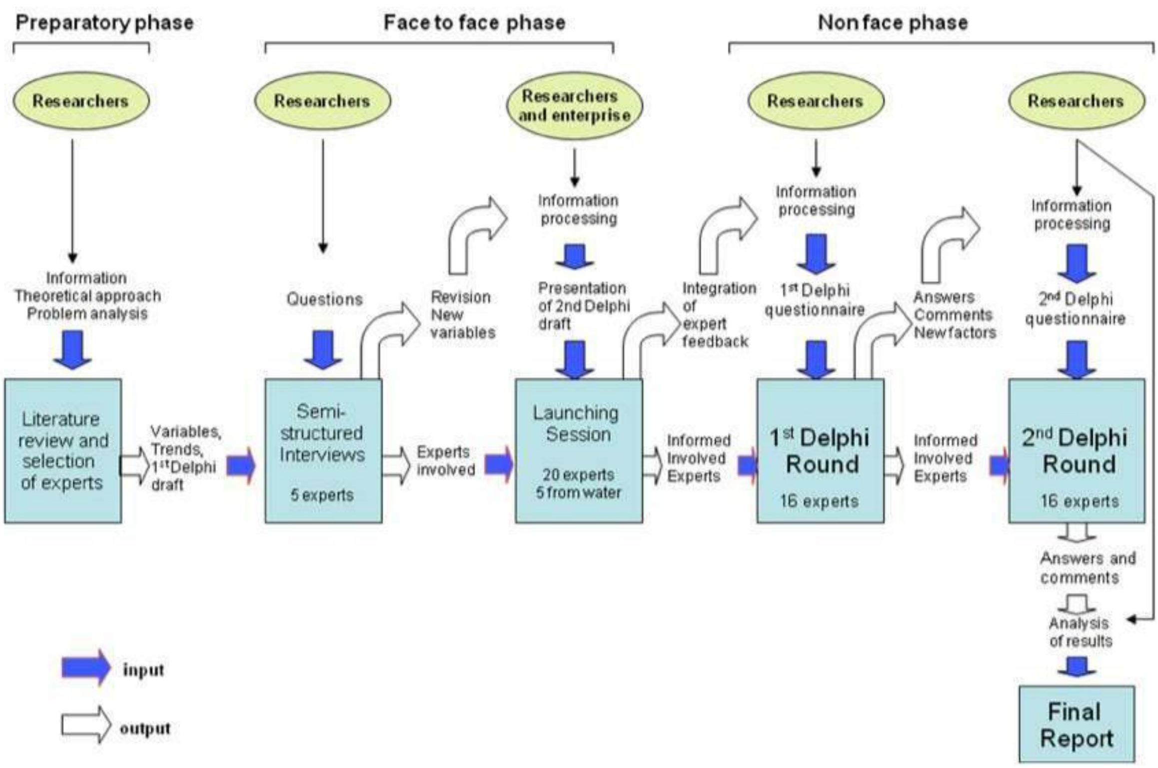


Fig. 3.1. Delphi research process. Source: adapted from Landeta et al. (2011)

3.3. Trends and results

This section will present the selected trends and aspects of uncertainty related to water security and water for energy posed to the experts for confirmation or refinement, as well as the results obtained from their answers. A list of the variables of uncertainty selected on the basis of the literature review and the elite interviews, as well as the questions posed to experts in the Delphi questionnaire is provided in annex 5.

For each aspect, first an introduction to the context and trends reported in the literature is provided, followed by the presentation of the results of the quantitative (mean, median and standard deviations) and qualitative responses given by Delphi experts.

3.3.1. Water security trends

3.3.1.1. Water demand and withdrawals by sectors

Context

Water demands are reported to follow an upward trend that will continue into the future both at global and sectorial levels. At present, in global terms, agriculture is responsible for 70% of water withdrawals, followed by industry (20%) and the urban sector (10%) (WWAP, 2012). These percentages vary among countries: in industrialized countries water withdrawals for industry can rise up to 50%, from which up to 40% are for energy production in some places like the United States (Granit *et al*., 2011). Global water withdrawals per sector as estimated by the International Energy Agency and the World Bank are presented in Table 3.1.

Sector	Water withdrawals in 2012 (km^3)	Future increase
Energy[1]	583	20 – 36% to 2035
Urban[2]	455	70 – 150% to 2050
Industry[2]	712	35 – 170% to 2050
Agriculture[2]	2,726	10 – 40% to 2050

Table 3.1. Predictions on the evolution of water withdrawals by sectors. Own elaboration from [1] WEO (2012) and [2]World Bank (2012).

The last estimates from the UN indicate that global water demand could increase by 55% by 2050, especially within the sectors of industrial manufacturing (400%), thermal energy (140%) and domestic use (130%) (WWAP, 2014). However, water consumption by the energy sector is believed to experience a sharper rise of up to 85% due to higher efficiency in power plants and cooling technologies, which reduces overall water volumes required but increases net consumption, and increasing biofuels production (Rodríguez *et al*., 2013).

Delphi results

Delphi results in Table 3.2 and Figure 3.2 report an overall rise of global water withdrawals in the future, with an average 20% increase compared to 2012 levels by 2030, and some 29% by 2050. The sharpest increases are registered for the urban and industrial sectors, reaching some 67 and 60% growth by 2050 respectively, though the high standard deviations suggest higher uncertainty or lower consensus among experts in these aspects. Agriculture and energy, with considerably lower standard deviations, are expected to follow a parallel 17-19% growth by 2030, to later slow down by 2050 reaching some additional 11% growth in the case of energy and barely 7% for agriculture. As can be seen, the share of the different sectors in total water withdrawals is expected to remain similar to the present. The resulting scenario is similar to some business as usual scenarios reported in the literature (WEO, 2012; OECD, 2012), as will be later discussed.

Sector	2030	2050	MSD*
Agriculture	17	23.5	8
Energy	19	30	7
Industry	39	60	21
Urban	40	67	24

* MSD: Mean Standard Deviation

Table 3.2. Percentages of increase in withdrawals by sectors. Own elaboration.

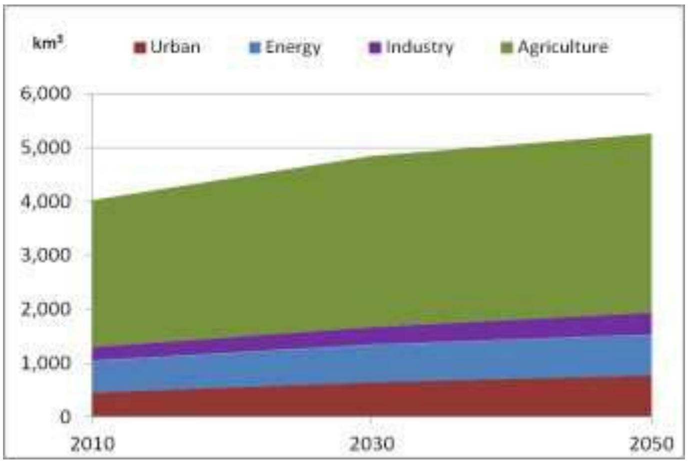


Fig. 3.2. Mean water withdrawals by sectors for 2030 and 2050. Own elaboration.

The qualitative comments from experts indicate that a generalized slowdown in the rise of water withdrawals identified for the period 2030-2050 is due to an expected improvement and generalization in water saving measures and technologies. This fact is seen as particularly important within the energy and agricultural sectors, where it might be accompanied by a rise in the water consumption rate, due to the expansion of intensive agriculture, dams, fracking and solar thermal energy. However, very high biofuel expansion scenarios are not seen as probable due to the widespread context of water scarcity, and also to important advances in the food industry, a reduction of losses in production chains and high competition with other sectors which might restrain agricultural demands. Within the industry sector, a clear distinction is made between developed countries, where improvements in water use efficiency and water saving technologies will allow for a stabilization or even a reduction of industrial water demand; and developing countries, where sharp industrial growth using traditional techniques will strongly increase demands and water quality degradation, especially in BRIC countries.

3.3.1.2. Water stress and water supply

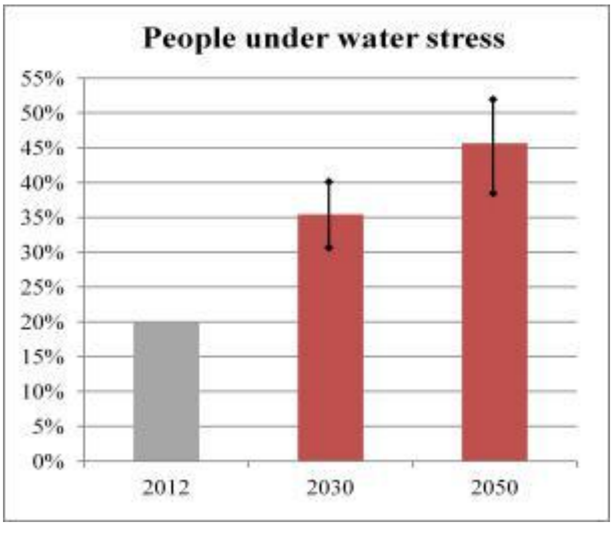
Context

Water availability constitutes a problem in many parts of the world due to the uneven geographical distribution of water resources and in certain cases limited access. Around 1.2 billion (10^9) people (around 1/5 of the global population) currently live under severe water stress conditions (water supply below 1,000 cubic metres per person per year) and another 500 million live in areas with risk to become water stressed in the near future (WWAP, 2014).

The evolution in recent decades indicates that water stress is increasing all over the world and will continue to do so in the coming years, due to increasing droughts, rainfall variability and glacier retreat caused by climate change (IPCC, 2014). Prospects to 2050 indicate that the percentage of people living under severe water stress conditions could rise between 40 and 60% (WWAP, 2014).

Delphi results

Delphi results in Figure 3.3 show consensus on an upward trend in the number of people living under severe stress conditions.



	2012	2030	2050
Mean	20[2]	35.44	45.63
Median	----	35.00	47.50
SD[1]	----	5.62	8.08

[1]SD: Standard Deviation

[2]Source: WWAP, 2012

Fig. 3.3. Evolution of the percentage of total population living under severe water stress conditions (<1000 m^3/person per year). Own elaboration.

Qualitative responses indicate that this rising trend could be motivated by several factors such as a generalized increase in urban, industrial and agricultural pressure on water quantity and quality, as well as the intensification of droughts, floods and desertification as a result of climate change. Management strategies, innovative technologies and virtual water trade are highlighted as essential means that could soften this trend in the most affected areas. In this line, one expert added that this situation should not necessarily lead to a rise in migration flows to other areas, partly because of the mitigating effect of technological solutions, and partly because borders will not be so easily opened. An expert calls the suitability of the 1000 m^3/person per year indicator into question, as personal water requirements vary significantly depending on cultural habits and local consumption.

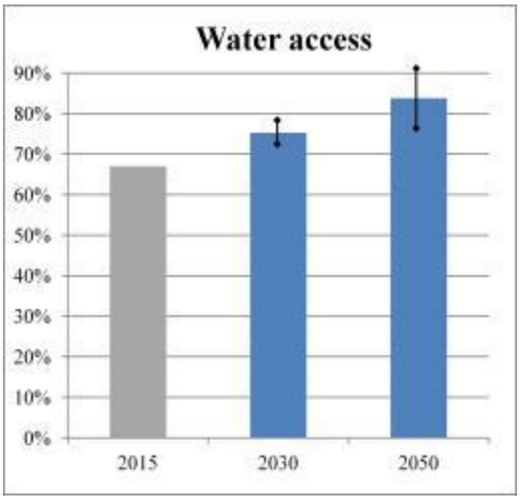
3.3.1.3. Water sanitation and treatment

Context

The average investments in water sanitation and treatment infrastructures in developing countries are low and many urban and rural communities still lack access to these basic services. In these countries, it is estimated that between 60% and 90% of wastewaters are not treated, thus causing severe degradation of rivers, aquifers and coastal waters (Corcoran *et al*., 2010). In spite of the international efforts to revert this situation, estimations suggest that the Millennium Development Goal of reaching 75% of global population connected to *improved sanitation facilities*[6] by 2015, would reach no more than 67% (UN Water, 2012). OECD scenarios place the number of people with access to sanitation between 80 and 90% by 2050 (OECD, 2012).

Delphi results for access to improved sanitation facilities

Results shown in Figure 3.4 indicate a high level of consensus on a future linear increase in the percentage of population with access to improved sanitation facilities, with average values of 75% by 2030 and 84% by 2050, and a mean standard deviation around 4.



	2015	2030	2050
Mean	67[2]	75.38	83.75
Median	----	75.00	85.00
SD[1]	----	3.12	4.51

[1]SD: Standard Deviation
[2]Source: WWAP, 2012

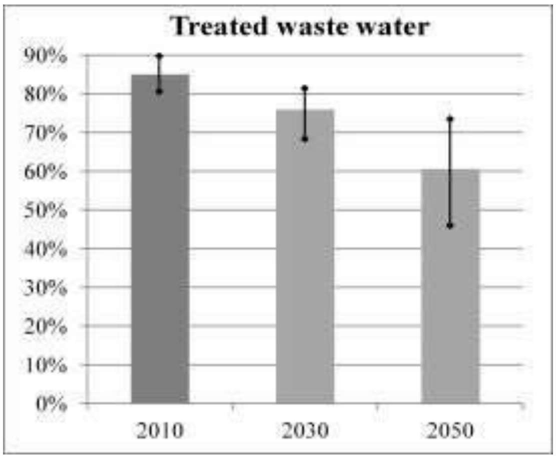
Fig. 3.4. Percentage of global population with access to improved sanitation facilities. Own elaboration.

[6] As defined by the World Health Organization (WHO), an *improved sanitation facility* is one that hygienically separates human excreta from human contact (United Nations Children's Fund [UNICEF]/WHO, 2015).

The survey qualitative comments highlight the importance of the concentration of growing population in cities and the support of nations and multilateral organizations as promoters of potential improvements. However, some experts consider that these upgrades will take place at a lower rhythm than expected, due to lack of institutional, technological and financial capacities in regions with lower access rates, low investment in maintenance of infrastructure, insufficient support from developed countries and spatial constraints to provide access to rural areas.

Delphi results for waste water treatment

Results in Figure 3.5 show a slow downward trend in the amount of untreated wastewater discharges in developing countries. This amount is expected to decrease down to around 75% of total wastewater by 2030, and further to around 60% by 2050. However, as reflected in average deviation values, a few experts consider it will remain constant around 70%, while another group accounting for 40% of the expert group believe it will be reduced down to 50%, showing in this case a lack of consensus.



	2010	2030	2050
Mean	80-90[2]	75.9	60.6
Median		75.0	57.5
SD[1]		7.8	13.5

[1] SD: Standard Deviation

[2] Source: WWAP, 2012

Fig. 3.5. Percentage of wastewater without treatment in developing countries. Own elaboration.

Within the qualitative responses, those experts estimating invariable percentages argued that increasing pollution rates and costs of water treatment infrastructure and technologies will impede advances in most developing countries, which lack solid institutions. Other opinions maintain that these are necessary investments that will need to take place, supported by international organizations and environmental treaties and legislation, and maybe through cooperation funds. Knowledge and technology transfer to developing countries was highlighted as a key factor in both cases.

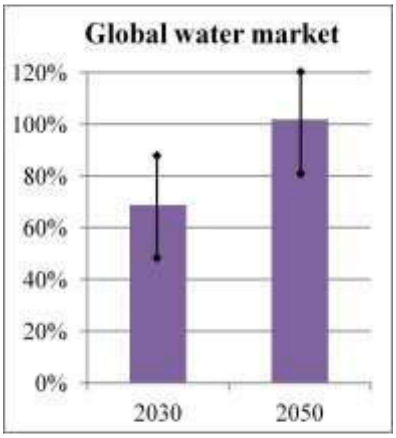
3.3.1.4. Global water market

Context

Several studies point to the water sector as a growing and promising market, highly attractive for international investments due to the rising demand in efficient irrigation and distribution technologies, smart metering, sanitation and water treatment technologies and desalination. Additionally, this market constitutes a path for technology transfer for developing and water stressed countries, envisioned to help create resilience against water scarcity, together with virtual water trade (Hoekstra & Hung, 2002). According to Deutsche Bank (Heymann *et al*., 2010), the global water market was worth between 300 and 400 billion (considering 1 billion as 10^9) euros in 2011 and it could double by 2035, reaching a growth rate of 100%.

Delphi results

As shown in Figure 3.6, there is high variability among responses regarding the future growth of a global water market. A 10 point difference is registered between the mean and median values (70-80) for the 2030 horizon, and standard deviations rise up to 20 in both cases. The results suggest that experts would place the time horizon for the water market to double its size in 2050 rather than in 2030-35, as predicted by Deutsche Bank studies (Heymann *et al*., 2010).



	2030	2050
Mean	68.75	101.88
Median	80.00	100.00
SD[1]	20.80	20.68

[1]SD: Standard Deviation

Fig. 3.6. Percentage of increase of the global water market. Own elaboration.

Qualitative comments pointed towards a quick growth trend of the water market in line with a growing population, economies and a need for new infrastructures. However, two important restraining factors were highlighted: the scarcity of the resource and the high infrastructure and technology implementation costs. Lower estimates were justified by the lack of guarantees for investors and the effects of cost recovery policies on the price of resources. Meanwhile, China and India are expected to play a key role and influence the markets, given the peak of demand and shortfall in resources.

3.3.1.5. Groundwater degradation

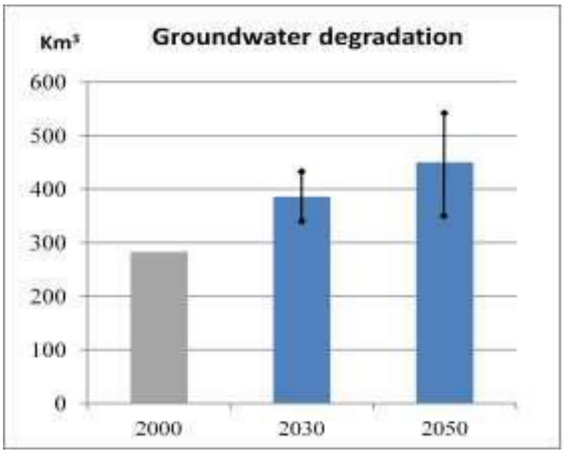
Context

Groundwater overexploitation is one of the most serious problems that could threaten water availability and environmental integrity. Groundwater exploitation currently has unsustainable rates in many arid and semiarid regions, like in India, Pakistan, the Western United States and China. At a global scale, the annual volume of water abstracted each year is estimated at 986 km^3, from which almost 70% is used for agriculture (WWAP, 2012). There is evidence that groundwater supplies are diminishing: as reported by Wada et al. (2010), groundwater depletion, defined as the volume of water abstracted at a higher rate than the natural recharge, has increased in the last decades from 126 km^3/year in 1960 to 283 km^3/year in 2000. At present, around 20% of world’s aquifers are considered to be overexploited (WWAP, 2012).

Meanwhile, as a result of climate change, most future groundwater assessment scenarios estimate a decrease of - at least - 10% in groundwater recharge rates by 2050 in semiarid regions (WWAP, 2012), which may reach up to 30% to 70% for the Mediterranean, north-eastern Brazil and south-western Africa (Döll, 2009).

Delphi results

Figure 3.7 shows a growing trend for groundwater depletion rates, though with marked variability especially towards the 2050 horizon. Average rates for 2030 and 2050 are around 386 and 450 km^3.



	2000	2030	2050
Mean	283	386	450
Median	----	400	500
SD[1]	----	44	100

[1]SD: Standard Deviation

Fig. 3.7. Groundwater depletion levels in km^3. Own elaboration.

Qualitative comments supporting higher depletion rate values put forward two main reasons: first, the strategy by a number of countries (India or North Africa) to create an economic model based on agricultural exports, and second, the 'common goods' nature of aquifers making it harder to achieve sustainable management. Moderate estimates are justified by a slowdown in this growth due to rising pumping costs driven by higher energy prices, and a social and regulatory reaction against the water quantity and quality degradation levels.

3.3.2. Water – energy trends

3.3.2.1. Water technologies and alternative resources

Context

The search for alternative water resources is becoming a constant, especially in regions with limited availability of fresh water resources (islands, arid regions,…) like the Mediterranean coast, where desalination and water treatment technologies are acquiring a key role to ensure water supply for certain sectors (WWAP, 2012). These technologies have high energy requirements that, together with the cost of technology itself, leads to non-competitive output water prices.

At present, total world desalination capacity is 24 km^3/year, which constitutes some 0.6% of global water supply (ETSAP & IRENA, 2012), expected to double by 2020 (H2O Middle East, 2012). In certain coastal and arid areas this share rises considerably: 24% in the Canary Islands (TECNOAGUA, 2011) or 15% in Israel, where the national roadmaps have set the objective to reach some 41% by 2050 (Tenne, 2010). The UN forecasts desalination to become cost competitive by 2040 (WWAP, 2012).

As regards water reuse, global water reuse rate, defined as the volume of water reused over the total volume of water treated, stands at around 5% (Lazarova, 2012). Some of the countries with higher reuse rates are Israel (70%), Singapore (30%), Spain (11%), Australia (8%) and the U.S. (6%). For Mediterranean countries, the average rate is expected to increase from 3.5% in 2005 to 13% in 2025 (Angelakis, 2012).

Delphi results

The results in Figure 3.8 show that both alternative water sources will present a slow growth in the future, though more substantial in developed countries. Desalination shows lower standard deviations than reuse, and is expected to follow a linear and limited growth up to 6.4% in developed countries and 4.2% in developing countries. Water reuse is expected to have a sharper growth, especially within the next two decades, reaching some 16.6% and 20% in developed countries and around 9% and 11% in developing countries by 2030 and 2050 respectively. Standard deviations for developed countries and developing countries are 5 and 3.5 for desalination and 9 and 8 for water reuse respectively.

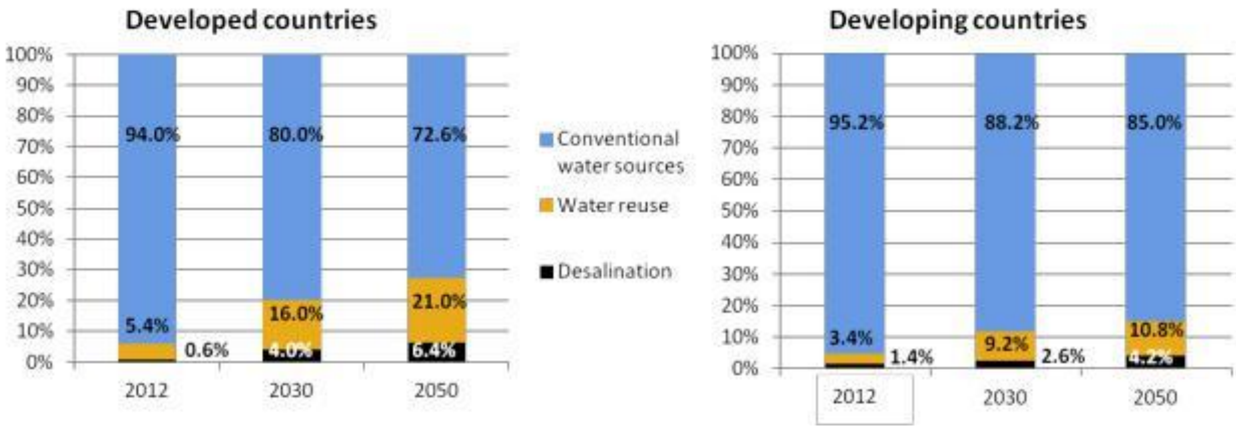


Fig. 3.8. Share of desalination and reuse water in 2030 and 2050 in total water supply in developed and developing countries. Own elaboration. Data for 2012 obtained from IEA-ETSAP & IRENA (2012) and Lazarova (2012).

Experts' qualitative comments regarding desalination suggest that, in spite of a progressive reduction of the production cost, this resource will not be able to compete with conventional resources, and will only have a market for uses with high economic value or for urban or industrial supply in coastal or semi-arid areas with high average rents. In developing countries it will be very limited due to bidding and funding problems. Nevertheless, two options were highlighted as especially promising: desalination of saline regenerated waters and solar energy and desalination coupled systems, especially within the Arab region.

As for water treatment and reuse, experts perceived them as a growing and necessary trend within water management policies in developed countries where, in spite of the costs, the already existing infrastructure will pose a comparative advantage over desalination. For the case of developing countries, opinions were more divergent. Some experts maintained that changes in environmental legislation, the need for resource optimization and foreign investments in reuse technologies will drive some growth. Others stated that the cost and infrastructural factors will be strong limitations, where a rising trend to reuse wastewater for agriculture without treatment may take the lead. Special remarks were made about the social perception, the emerging pollutants problems and the need to adjust the necessary quality for different uses, where technological improvements are seen as the key to enable a safer and more attractive resource.

3.3.2.2. Impact of energy types and technologies on water

Context

The need for water to produce energy has been widely recognized as a possible future limitation to ensure energy security. Soon the different water withdrawal and consumption rates could become the determining aspect for technology selection. However, available data on water performance of energy technologies are still vague, with wide value ranges and variability depending on local conditions like climate, type of cooling technologies or waste water management practices (Rodríguez *et al*., 2013). Meanwhile, water quality related aspects are frequently neglected, and assessment and monitoring practices are seldom applied (Rodríguez *et al*., 2013).

Delphi results

Tables 3.3 and 3.4 show that, as perceived by experts, biofuels will have the highest future impacts on water quantity and quality, together with shale gas extraction for the quality aspect. Nuclear and thermoelectric energy are attributed similar intermediate impact levels on both aspects. Hydrogen batteries get a rather low perception of impacts on water quality and particularly on water quantity, only above hydropower which is at the bottom of the list of water quality impacts, and with moderate, but far from negligible, impacts on quantity. Average deviations oscillate between 1 and 1.5.

Impacts on quantity	LEVEL OF IMPACT (1>2>3>4>5>6)	
	2030	2050
Biofuels	1	1
Thermal power	3	3
Nuclear	3	3
Shale gas	4	4
Hydropower	4	4
Hydrogen batteries	5	5

Impacts on quality	LEVEL OF IMPACT (1>2>3>4>5>6)	
	2030	2050
Biofuels	2	2
Shale gas	2	2
Thermal power	3	3
Nuclear	3	3
Hydrogen batteries	4	4
Hydropower	6	6

Tables 3.3. and 3.4. Level of impact on water quantity and quality of different energy types and technologies. Own elaboration.

Most of the experts indicated in their qualitative comments not to feel qualified to make estimations about the future energy mix composition, but some valuable considerations regarding future issues for water quantity and quality were provided.

Regarding water quantity, one of the highlights referred to the considerably low consumption rate of hydropower, even considering the evaporation losses, as compared to the other energies and especially to biofuels. One expert also noted that shale gas and batteries could considerably increase their percentage share, thus increasing their net impact. Another expert stated that small changes in production techniques will not substantially modify the water requirements of energy technologies, and overall impacts will rather rely on international policies and support for each technology.

As regards water quality, three aspects were particularly emphasized: first, the high uncertainty and potential threats to water quality from biofuels – due to the massive use of fertilizers – and from shale gas. Second, the less known importance of thermal disturbances and pollutant or nutrient concentration effects in uptake and discharge points associated with thermal and nuclear cooling. Third, the important river flow and hydrodynamic disturbances caused by the 'sequestration', lateral diversion and irregular releases (hydropeaking) of water by hydropower, with additional downstream environmental effects.

3.3.2.3. Shale gas

Context

The production of shale gas using hydraulic fracturing techniques has experiencing an upward trend over the last decades, particularly in the U.S., China and Eastern Europe (IEA, 2011b). This technique has been reported to pose risks for water quantity and quality if the appropriate precautions and best practices are not strictly applied.

Impacts on water quantity derive from the volumes required to stimulate the wells, which usually range between 2 and 6 gallons (10,000 to 20,000 litres) per well (NETL, 2014). Potential impacts on water quality include migration of methane strays to shallow aquifers, hydraulic fluid spills or leakage from well fissures (Cooley 2012).

Delphi results

Results in Figure 3.9 shows high diversity of opinions on the degree of impact that hydraulic fracturing has on water quantity, though a downward trend in time can be observed. Regarding impacts on water quality, there is higher agreement on a medium to high level of impact, though the trend in time again points to a decrease towards the future.

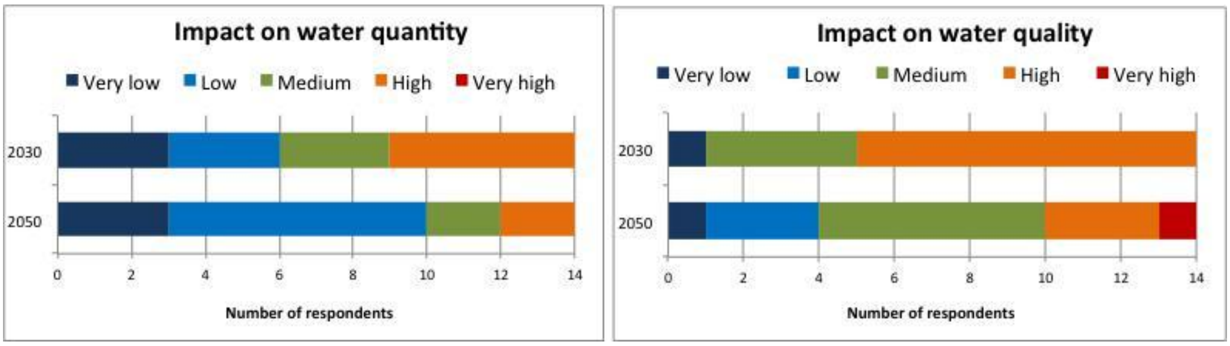


Fig. 3.9. Valuation from experts of the potential impacts of hydraulic fracturing on water quantity and quality. Own elaboration.

Qualitative comments show agreement on a continued rising trend of shale gas resource exploitation, particularly in developed countries with high dependence on imported energy. As regards to the impact, most of the experts think the impacts can be important, although the impact magnitude is still not clear. The impacts will highly depend on the local and geographical context and the expansion of the activity, acquiring greater relevance in arid and semi arid regions. One expert considers that - regardless of the technical and efficiency advances - certain impacts on the environment cannot be prevented and will be difficult to compensate. Another expert disagrees with the resulting trend line, arguing that - regardless of the intensity of the activity - the quantity of water required would be always low compared to other energy types.

3.3.3. Food security trends

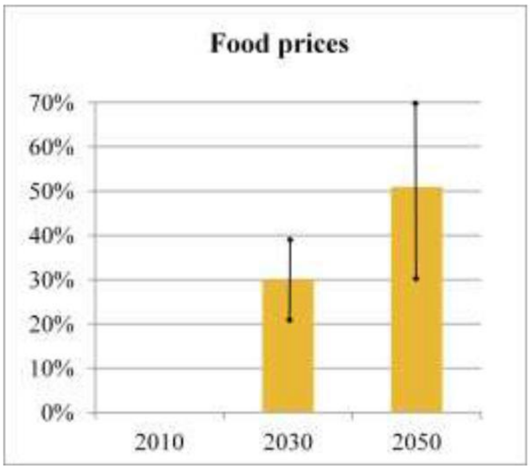
3.3.3.1. Food prices

Context

Food prices have been experimenting high volatility over the last decade. Especially noticeable were the episodes between 2007 and 2009, with increases from 20% in meat products up to 80% in vegetal oils (Lamos, 2010). In the present context, it seems probable for this trend of instability and progressive rise in food prices to be maintained, posing a threat to food security in many regions. Growth estimates for actual food prices range between 40% and 130% by 2050 (Nelson et al., 2010).

Delphi results

Figure 3.10 shows a growing trend over time, with considerable variability in the answers, as can be seen by the standard deviations. Compared to the reference scenario provided, which considers a range of 40% to 135% increases, most of the experts have opted for moderate forecasts, with average estimates between 40% and 50%.



	2010	2030	2050
Mean	0	30.0	51.0
Median	----	30.0	50.0
SD[1]	----	11.4	21.0

[1]SD: Standard Deviation

Fig. 3.10. Percentage of increase of food prices compared to 2010 levels. Own elaboration.

Qualitative comments supporting the most extreme predictions (over a 75% increase) point out to the rise in per capita incomes and consumption - which will favour the food industry business -, the effects of competition with biofuels and speculation as the main reasons. Reasons for more moderate predictions include the existence of sufficient capacity and productive potential to cover food demands, as well as improvements in the productivity and efficiency along the whole supply chain. However, a certain increase will be inevitable due to the need for pay back on new technologies. Important factors identified are payment capacity, speculation and oil prices, the last one very influenced by the future evolution of the shale gas market.

3.3.3.2. Cultivated land surface

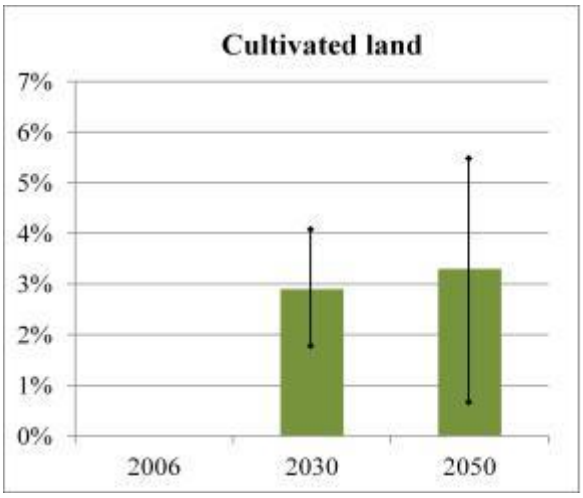
Context

The trends in population growth and rising food demand will bring the need to increase agricultural production over the following decades. There is uncertainty over how this will impact the land surface devoted to agriculture, depending on the action lines to be developed by the agricultural sector. In a study made by Bruisma (2009) the global surface of cultivated land in the world will increase an average 5% by

2050. Another study by Nelson et al. (2010) considers a possible scenario driving a 3% decrease over the same period.

Delphi results

The high number of factors influencing this variable is reflected in the results obtained and presented in Figure 3.11. In the short term, most of the experts forecast an increase in the cultivated land surface area, though with variations between 1% and 6% (equivalent to 14 and 83 million hectares respectively). In the long-term there is not a clear consensus among experts, as shown by the high standard deviations, with estimates ranging from an increase of 10% to a stable or even decreasing trend.



	2006	2030	2050
Mean	0	2.9	3.3
Median	----	3	3.5
SD[1]	----	1.2	2.4

[1]SD: Standard Deviation

Fig. 3.11. Percentage of increase of cultivated land surface compared to 2006 levels. Own elaboration.

Qualitative comments and reasons vary considerably. Experts supporting an increasing trend identify as causal drivers the rising food demand, prices and productive pressures, since there is margin for growth and intensification. A second line of opinions considers that the increase will be limited by soil availability constraints, which are dependent upon the conservation policies applied. Nevertheless, the expansion of cultivated lands in areas with low protection (like Africa) may be offset by the decrease in others with higher restrictions (like Europe). A third line of opinions considers that the trend will go towards the intensification of existing agricultural holdings and an advancement and innovation in agro-food technologies rather than to an expansion of the agricultural surface.

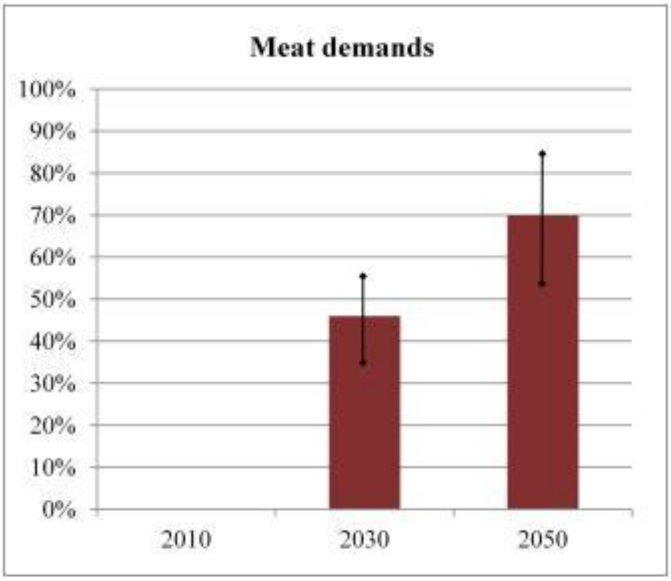
3.3.3.3. Consumption patterns

Context

Increasing life standards and economic power in BRIICS countries (Brazil, Russia, India, Indonesia, China and South Africa) is driving a shift in consumption patters towards livestock products which are more water intensive. As a result, world meat demand is expected to increase between 70% and 100% by 2050, compared to 2010 levels (FAO, 2011).

Delphi results

Results in Figure 3.12 show expert agreement on a linear growth for meat demand in the future. By 2030 this variation may hover around 40%. By 2050, experts place their predictions close to FAO (2011)'s reference scenario, though slightly below the 100% figure.



	2010	2030	2050
Mean	0.0	46	70
Median	----	40	70
SD[1]	----	11.6	18.5

[1]SD: Standard Deviation

Fig. 3.12. Percentage of increase of meat demands compared to 2010 levels. Own elaboration.

Qualitative comments which support the highest increase are based on the evidence that the increase in meat consumption is closely linked to urbanization and better life standards. These factors are particularly intensifying in regions with higher population growth prospects.

More moderate opinions argue that the high water footprint of meat products will limit their production in water stressed areas, as well as the promotion of new consumption patterns (awareness campaigns, responsible consumption, vegetarianism), summing to the fact that the traditional diets of these countries (i.e. India) are less meat intensive. Some relevant points noted include the high dependence on the price of food commodities as well as on the type of meat products to be promoted (not all meat products are equally water intensive). A final remark pointed out that the higher challenge lies on developed countries, where consumerist habits are more deeply rooted.

3.4. Evaluation of the Delphi study performance

The experts rated their level of knowledge as high in all the questions, with a mean value of 3 over 4. The participation rate was 40% of the experts invited, which can be considered as high given the voluntary and non-rewarded character of the study, (Dalkey, 1969). In the second round, 70% of the questionnaires were revised and resubmitted. For the other 30%, the answers given in the first round were considered as final. When analysing the differences between the answers in both rounds, it was observed that most of the experts maintained their initial answers, except for those cases where their estimates varied far from the group median values. For those cases, two main answer modification patterns were identified: experts indicating low expertise level on the particular question tended to exchange their answer for the group median value; experts indicating high level of expertise on the question tended to slightly modify their answer to approach the median, but maintaining the initial identified trend. For the case of questions left unanswered in the first round, some experts opted to adopt median values while others refrained from answering. These behaviours prove the technique is able to change experts' opinion according to their level of knowledge and confidence, through the provision of group statistics and qualitative arguments, reaching a final opinion of presumable higher quality than the mean of individual initial responses.

3.5. Discussion of results

Looking at the results and in view of the last UN World Water Development Report on water and energy launched the 22nd March 2014 (WWAP, 2014), some aspects are worth analysing.

First regarding *water withdrawal predictions*, the scenario resulting from Delphi experts' responses envisions a similar increase, though slightly lower, to OECD's and UNEP's business as usual scenarios in terms of global withdrawal increase to 2050. Yet, predictions from Delphi experts for the industrial and energy sectors are considerably lower, based on the trust in the potential improvements from technological efficiency and water saving policies. Meanwhile, this technological efficiency would drive a rise in energy consumption. Estimations of water for energy to 2030-35 stand in line with the IEA's New Policies Scenario, with a 20% rise (WEO, 2012). For the case of agriculture, contrary to OECD and UNEP scenarios that predict agricultural water withdrawals to remain stable or reduce, Delphi experts foresee a 23% rise to 2050, compared to 13% estimated by International Water Management Institute (IWMI) (Molden, 2007) and 11% by Food and Agriculture Organization (FAO) (FAO, 2011). The importance given by WWAP (2014) to potential biofuel expansion could support these higher estimates indicating that biofuels are a key variable to mention in relation to overall global water/energy scenarios. In this respect, responses from elite interviews highlighted that the important problems will arise at regional and local scale, with the Sub-Saharan and Asian regions especially affected. However, experts also consider that catastrophic scenarios might not be as hard as predicted for water, since there are tools to help address water scarcity such as technology, international trade and changes in consumption patterns.

Second, in terms of *future impacts of energy types on water resources*, bringing together the evaluation made by Delphi experts and the main highlights from WWAP (2014) on trends in energy technological development, four energies emerge as potentially outstanding: biofuels, shale gas, thermal power and hydropower.

Biofuels are predicted to expand considerably, especially in the Asian region (WWAP, 2014), where water scarcity and water pollution problems are particularly acute. However, some Delphi experts are sceptical about the high biofuel expansion scenarios, considering these unviable within the context of water stress in such regions. They argue that the driver that will define these scenarios is the speed of innovations in low water consuming 2nd and 3rd generation biofuels, which are expected to enter the market by around 2025 (Rosegrant *et al*., 2008; Gerber Leenes *et al*., 2012).

Shale gas production has taken off in the U.S. and the ground is being prepared in the European Union, waiting for a benchmark that can set the guidelines for safe performance. Energy independence is a strong incentive for the development of this technique in Europe, but possible impacts on water quality will constitute a big constraint, even more than quantity requirements according to Delphi experts, as these may be overcome with possible future innovations to reduce water use by reuse or recycling. After some incidents registered in the U.S., recent studies suggest that most of the problems related to water quality were due to failures in well construction and integrity and accidental spills during operations (Puls, 2014). Thus the development of stringent regulations on protective measures, operating procedures and monitoring programmes should be an essential priority in regions where this activity is barely starting, like in the case of Europe. However, equally important will be the necessary role of water and energy management institutions to ensure effective implementation and compliance with these regulations, which will require coordination, investment in qualified professionals and bureaucratic and informational transparency.

Thermal power is perceived by Delphi experts as the third most impacting energy source. At present, thermal power accounts for roughly 80% of global electricity production (IEA, 2014). The main impacts on water from thermal energy are as a result of the cooling process, and depend on the type of cooling technologies employed. A shift towards more water efficient cooling systems in the future could help reduce water withdrawal requirements from this type of energy, but would also entail an increase of water consumption (Delgado, 2012; DOE, 2014).

Hydropower is considered to have a considerable potential for expansion, particularly in Africa, Asia and Latin America (WWAP, 2014). According to the IEA (2012), by 2050 global hydropower capacity installed could double and most of it will be developed in those regions. Acknowledging that overall impacts on water quantity may not be substantial (although this should be checked out for regions with very high evapotranspiration rates), Delphi experts warn of the impacts derived from the local withdrawals of water, which can threaten water quality, ecological flows – and thus aquatic ecosystems – and the availability for a clean water supply downstream for other users. In fact, this could be applicable to both macro and micro hydropower, since both generate impacts that should be closely studied when making decisions on the best technological road to take, as illustrated by Abbasi and Abbasi (2011).

Third, *desalination* is seen by Delphi experts as an expensive and energy-costly solution that may only be an option in certain coastal areas with critical supply threats, and for specific uses with high economic revenues. This is confirmed by the situation in some Middle East countries, where for several cities the joint cost of desalination and pumping of water to urban areas is very high (WWAP, 2014). However, this technology is increasingly regarded as an opportunity when combined with renewable energies. New opportunities for desalination are also emerging within the oil and gas sector, where the need to find alternative solutions to dispose of saline-produced waters is driving intense technological research.

As noted by experts, reused water seems to have greater potential. The possibility to recover energy in wastewater treatment plants is an increasing trend emphasized as a way to reduce production costs (Environmental Knowledge Transfer Networks (KTN), 2008). Other remarkable trends to overcome this problem include combined water-energy production systems (e.g. water-energy-nutrient farms in the Netherlands (Stowa, 2010)) and renewable energy coupling to desalination plants or heat and energy recovery systems (WssTP, 2011). However, the adjustment of quality levels to the requirements of different target uses is highlighted by Delphi experts as a critical factor for its economic competitiveness.

Fourth, regarding food security aspects, food demand will continue to grow towards higher consumption of livestock products in emerging economies, though without reaching the current levels in western countries. This demand will probably be covered by increasing resource efficiency and productivity in all stages of the production and supply chains, and through technological advances and innovation. This will also contribute to maintain the surface of cultivated land relatively stable. Food prices will keep on rising, spurred by electricity prices and the need for technological cost recovery, though these will remain closer to the most moderate growth predictions. Critical factors conditioning the future of food prices stability will include speculation, oil prices fluctuations and policies on agricultural subsidies.

Finally, *infrastructure and technology* stand out as key factors to improve access to water and sanitation, attract water and energy related investments and secure water and energy provision (WHO, 2014). Investments in water and energy infrastructure will mean resilience for the future, but they should be accompanied by smart cost recovery policies, incentives and subsidies to make them economically sustainable. Meanwhile, the importance of technology and knowledge transfer is highlighted as a cross-cutting aspect that can make the difference in the road taken by developing countries: an aggressive development entailing severe environmental and resource degradation, or a conscious development promoting impact prevention and mitigation.

3.6. Conclusions and policy implications

Reducing uncertainty on the future evolution of critical variables affecting water and energy security is a difficult task, where subjectivity and considerable margins of error will always be present. However, some knowledge is better than no knowledge (Helmer, 1983).

This study shows that experts identify an overall increase of pressures on water resources, both in terms of quantity and quality, especially in developing areas with high water stress and population growth. Experts outline a scenario between the 'business as usual' and the 'sustainable world' visions, with technology innovation and transfer as key catalysers of energy and water security. In developing countries, the substantial investment needs for infrastructure enhancement and maintenance, together with the lack of solid institutions and political will, pose the biggest challenge for the achievement of the Sustainable Development Goals. Alternative water resources such as desalination and reuse will only contribute to ease water stress in very specific areas and for certain uses. Only water-energy coupled solutions may help overcome the high energy cost limitations. In terms of energy, the evolution and expansion of biofuels and shale gas will be a key energy determinant for impacts on water resources. However, this expansion will depend upon the capacity and speed of technological innovation to reduce these impacts, in order to avoid becoming simply constrained by the context in certain regions.

From a political standpoint, two essential messages should be drawn from the study: the importance of considering water as a limiting factor in decisions on future energy roadmaps; and the essential role of well-maintained infrastructures and technological innovation to build future resilience.

As a final remark, it should be noticed that UN type assessments and expert opinions are based on the study of past trends, experience and best guesses. However there is always the risk that unforeseen and disruptive events (i.e. low probability but high impact) may alter these projections.

CHAPTER 4

APPLICATION OF A WATER-ENERGY-FOOD NEXUS FRAMEWORK FOR THE DUERO RIVER BASIN IN SPAIN

Chapter 4. Application of a water-energy-food nexus framework for the Duero river basin in Spain

4.1. Introduction

As it has been already mentioned, within the intense nexus debate some of the most important topics discussed refer to the lack, dispersion and imprecision of data for both water and energy accountings; poor knowledge on interconnections and their consequences, as well as the interactions with other driving forces such as food security or climate change; and how to best deal with these problems through the implementation of integrated management policies. Among these challenges, the need for action on the implementation of integrated policies is acquiring crucial importance, since it has been recognized as an essential condition for success in the achievement of the Sustainable Development Goals and climate change adaptation frameworks (UNW-DPAC, 2015a).

The Spanish case is a good example conveying several examples of water-energy-food nexus trade-offs and interconnections, where independent and uncoordinated sectoral policies have led to diverse resource management conflicts. A particularly sound example is the Irrigation Modernization Plan implemented by the Spanish government between 2002 and 2008: an investment of 5024.57 million euros was made to modernize 1,134,891 ha (a third of the irrigated area) with the aim to achieve 2100 Mm^3 of water savings (López-Gunn et al., 2012a). The lack of pre and ex-post evaluations of potential cross-sectoral unintended consequences driven by water-energy interdependencies, as well as the lack of intersectoral institutional coordination to react to the outcomes, have brought a great part of the Spanish agricultural sector to the limits of its economic sustainability. A rebound effect on the use of water caused a lower than expected or even non-existing amount of water savings in many provinces (Dumont et al., 2013). Meanwhile the increase in energy consumption and energy dependence for irrigation in a context of rising energy prices, has constrained farmers' livelihoods all over the country (del Campo, 2014). This example illustrates the need for further efforts to analyse and understand nexus interconnections in order to elaborate informed and coordinated policies.

In this context, this chapter aims to present a conceptual framework for the WEF nexus approach based on an analysis of existing conceptualizations, as well as to propose an assessment methodology to guide implementation at the basin level. This methodology is then applied to the case study of the Duero river basin in Spain to illustrate how it can help understand the trade-offs and synergies, diagnose the level of political coordination, and identify existing and potential solutions to improve WEF resource management in the region. A scientific article based on this chapter was produced and published in a special issue on the nexus by the Water International journal in June 2015 (see annex 1).

4.2. The WEF Nexus framework and assessment methodology

Within the present debate about the water-energy-food nexus, one of the main goals is to define the scope and framework of the water-energy-food nexus concept.

Chapter 2 has presented a review of existing WEF frameworks, reflected on the nature of the nexus and presented a definition and conceptualization for the WEF nexus concept as understood by the author of this thesis. The WEF nexus concept is understood as 'the set of interconnections, trade-offs and interdependencies existing between water, energy and food as a result of their natural cycles and human use'.

As argued in chapter 2, most of the existing nexus frameworks are aimed to facilitate improved resource management at the political and institutional scales to achieve water, energy and food security. The Nexus approach as defined in this thesis shares this goal; it is aimed at and allows to understand and quantify the complexity of the interconnections and flows between the three resources and sectors, in order to promote informed and coordinated resource management (see Figure 2.9 in chapter 2).

However, a complete WEF nexus framework should not be restricted to the political and institutional levels, since resource management is also required at business and household levels. It should be framed and applied in order to build resilience[7] at all scales, spanning across an enterprise business model or an industrial production process at the individual level (e.g. a livestock farmer).

To make this framework functional and applicable to support decision making at a regional or context specific scale, a methodology is here presented that is based on the two pillars of the WEF nexus concept: understanding and coordination. This methodology consists of the following steps:

1. *Identification, accounting and description of main trade-offs:* identifies and characterizes the flows and impacts to detect the main trade-offs and conflicts. Here impacts on water quality will also be analysed, as water quality degradation is an essential factor that can constrain water availability in a basin, as well as disturb the integrity and functioning of the whole ecological system (Karr, 1991; WWAP, 2012). The inclusion of water quality considerations and analysis is a key element for a full characterization of the WEF interconnections that allows for the effective identification of interrelated impacts and conflicts (WWAP, 2014; Rodriguez, 2013).
2. *Analysis of the level of integration and coordination of sectorial policies and institutions.*
3. *Discussion of the existing and potential strategies to mitigate conflicts and promote synergies:* identifies existing mitigation initiatives and provides a discussion on the results of the analysis to identify possible solutions.

The application of this assessment methodology will allow policy makers to detect problems derived from the WEF nexus in a basin, evaluate the potential for improvements in policy coordination and explore preventive and mitigation solutions to reach a win-win sustainable use of water, energy and food resources. As an illustrative example, in the next section this methodology is applied to the case of the Duero River Basin in Spain.

[7] Resilience is the capacity of a system to absorb changes and tensions without collapsing and losing its functionality (Holling and Gunderson, 2002).

4.3. Application of the WEF nexus framework for the Duero basin in Spain

The Duero Basin is the largest transboundary system in the Iberian Peninsula, covering an area of 98,073 km^2 (de Miguel et al., 2012) (see Figure 4.1). Born in the Iberian Mountains, it runs through Spain and Portugal along 913 km (770 km in Spain and 143 km in Portugal) and ends in Porto at the Atlantic Ocean (CHD, 2012). This study will focus on the Spanish part of the basin, which accounts for 80% of its surface area (78,859 km^2). The Spanish Duero basin has a population of 2,200,000 inhabitants and has experienced remarkable ageing and 'deruralization' over the last several decades (CHD, 2012).

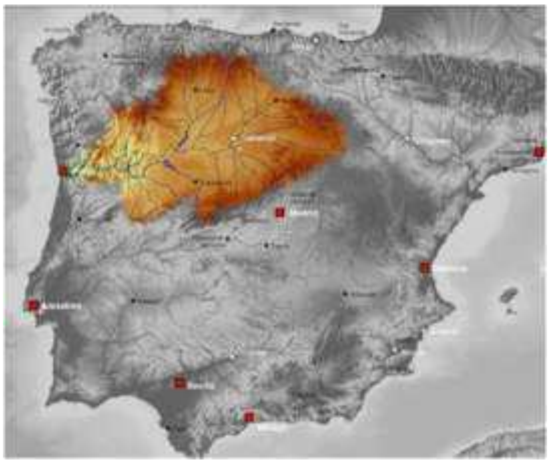


Fig. 4.1. Location of the Duero River Basin in the Iberian Peninsula. Source: Wikimedia Commons.

The Spanish Duero basin has average precipitation of 625 mm/year resulting in 13,600 Mm^3 of available water. Agriculture and energy production (especially hydropower) are the most important water users, concentrating respectively over 85% of consumptive[8] water demand and over 90% of non consumptive water demand. Within the national context, the basin plays an important role for the country's energy and food production. The hydropower capacity of the basin provides around 25% of the national energy supply. Meanwhile, local agricultural production of grain, which hovers around 7 million tons (5.4 million tones in rain fed areas, 1.6 million tons in irrigated areas), accounts for 24% of national production. However, in a region with periodic droughts, such demands have led to competition for water resources in certain periods in the last decades, as well as problems of drastic natural flow regime variations and ecosystems degradation. This has resulted in stricter regulation on the maintenance of minimal ecological flows (Morán-Tejeda et al, 2012; Paredes et al., 2011). Within the context of the Water Framework Directive, in depth studies to characterize these problems and design corrective and regulatory measures have been undertaken by the River Basin Organisation (RBO). The Duero Hydrological Plan approved in 2013 included some of these measures, such as the establishment of compulsory minimum ecological flows for each river stretch to ensure aquatic ecosystem integrity, with other improvements to be incorporated in the revision phase of the plan in 2015 (CHD, 2012). In this context, the identification and characterization of trade-offs among water, energy and food resources can

[8] Consumptive use of water is defined as 'water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment' (Vickers, 2001).

be particularly useful for planning processes at basin and regional levels to secure regional environmental integrity and regional and national food and energy supply security.

4.3.1. Step 1. Identification, accounting and description of the main trade-offs and conflicts among the three sectors

For the accounting of WEF flows, we first present a series of concepts used by water accounting methodologies (Hoekstra et al., 2011), which will be used for water flow characterization. These concepts are as follows:

- *Blue water*: water contained in rivers, lakes, aquifers and wetlands (Molden, 2007). Withdrawn blue water can be given a consumptive or non-consumptive use depending on whether it is returned to the environment or made available for further use in the same geographical system (Hoekstra et al., 2011).
- *Green water:* water from rain and stored as soil moisture (Molden, 2007).
- *Water consumption (WC):* water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment (Vickers, 2001). Water evaporated, either by evapotranspiration or by direct evaporation, is here considered as non-available for further use within the basin system, provided that this water can physically migrate to other regions when entering the global atmospheric cycle. The same applies to water diverted into the sea.
- *Water withdrawal (WW):* water diverted or withdrawn from a surface water or groundwater source (Vickers, 2001; Hoekstra et al., 2011). According to this definition, WW makes reference to blue water abstraction, when water is physically diverted or taken from a water source, to be given either a consumptive or a non consumptive use.

4.3.3.1. Water for energy

Current energy production in the area relies mainly on hydropower and coal-fed thermal energy, though a solar thermal power plant is projected to start working in 2015. Hydropower is the major source of energy in the region, with an installed capacity up to 4000 MW –around 20% of national capacity- and an average production of 9300 GWh/year. Water consumption is mainly caused by evaporation losses from the biggest dams, namely *Almendra* dam and *Ricobayo* dam, which have storage capacities of 1179 and 2586 Mm^3 respectively, with losses estimated at around 250 Mm^3/year from both reservoirs (CHD, 2012).

Thermal energy production is concentrated in two power stations which account for 1,171 MW of installed capacity, with annual production reaching 1763 GWh in 2009. The water withdrawal requirements for cooling these stations account for 162 Mm^3, from which 30 Mm^3/year are consumed (CHD, 2012). In addition, another combined cycle thermal power station of 920 MW capacity will be operative in 2015, with a second expansion for an additional 920 MW, which will incur in additional 7 Mm^3/year of water withdrawal for 2015, which will increase to 11.3 Mm^3/year after future expansion. Meanwhile, a new solar power plant of 100 MW capacity will require some additional 845,000 m^3.

There are some additional small scale biomass power stations with low installed capacities and annual production rates, whose water requirements have been reported as negligible due to their small size and use of dry or closed loop cooling systems.

The overall water required for energy production for 2015, according to the estimations made in Duero's Hydrological Plan, is summarized in Table 4.1. The calculation of water for energy was performed on a 2015 scenario basis in order to allow the inclusion of the new energy developments that will be operating shortly. Note that all the water consumed by energy is blue water, as it comes from rivers or groundwater.

Type of energy	Water Withdrawals (WW) (Mm^3)	Water Consumption (WC) (Mm^3)
Hydropower	83,700	250
Thermal	174	30
Solar	0.845	0.14
TOTAL	**83,874.85**	**280.14**

Table 4.1. Estimation of water withdrawals and consumption by the energy sector in a 2015 scenario for the Duero Basin. Source: Own elaboration from CHD, 2012 and CHD, 2014a.

Parallel to water consumption, another important trade-off derived from the use of water by energy and often not considered is the impact on water quality.

For the case of thermal energy, impacts are mainly related to the discharge of cooling water back into the river, usually at a higher temperature than the receiving waters. There are three thermal discharge points and two additional minor discharges coming from small biomass power plants (Figure 4.3). Only one of the cited discharges flows into a water body classified as *good ecological status* required by both European and Spanish legislation.

For the case of hydropower, the most important impacts caused by large scale installations are associated with the dams and include flow regime disturbances, water quality degradation in the reservoir as a result of stagnation, decrease of lateral flows in some river stretches and impacts on the aquatic and riverine ecosystems (CHD, 2012). Besides the large dams, the Spanish part of the Duero river accounts for a large number of smaller dams that were historically created to divert water into the irrigation channel system. Today, more than 3500 small dams have been registered along the river (CHD, 2012). Associated with some of these smaller dams are several small scale hydropower stations. The main impacts caused by these small dams are a reduction of river flow velocity (to the point of shifting the lotic system into a lentic system in certain stretches), impacts on aquatic fauna and alteration of some water quality parameters like temperature, turbidity and dissolved oxygen (CHD, 2012).

Figure 4.2 shows the location of the different power plants and the 288 hydropower stations in the Spanish part of the Duero river and tributaries of which only 163 remain operative, with 3,846 MW of installed capacity and 6,874,135 MWh of annual production (CHD, 2011). The remaining 125 hydropower plants have been either stopped temporally or dismantled due to the expiration of their operation concession. This process was driven by an in depth revision of all hydropower concession contracts started in 2008 by the Duero RBO, in view of the confluence of a high number hydropower concession deadlines within a period of five to eight years. In this revision process the conditions, compliance with required ecological and functional standards, and endurance of existing hydropower contracts were assessed. As a result of this revision, only those hydropower plants meeting the standards or applying the required mitigation measures had their concessions renewed, leading to the reduction in operative power plants mentioned above (CHD, 2011).

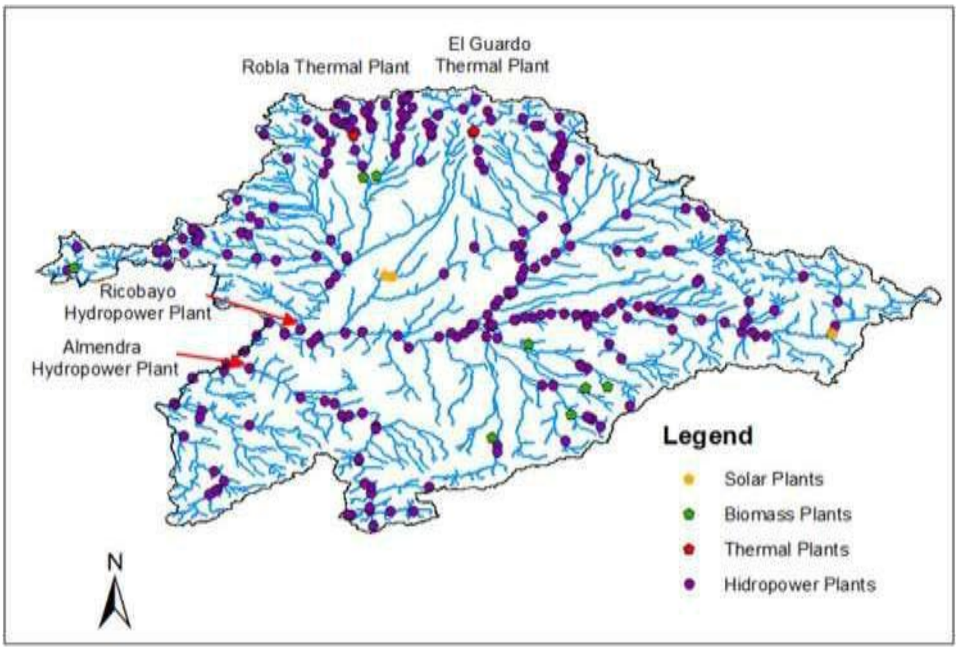


Fig. 4.2. Location of the different types of power plants along the river basin.

Source: Own elaboration with data from Mírame Database.

4.3.3.2. Water for food

Water use for food production in the region is mainly caused by agriculture, which accounts for more than 80% of the water demand within the basin (CHD, 2012). Other water consumption activities related to food production in the basin are livestock, food processing industries and aquaculture.

Total agricultural area in the basin is up to 4 million ha, 3.5 million ha being occupied by rain fed crops and 0.5 ha by irrigated crops (CHD, 2012; Paredes et al., 2011). In contrast with other uses, agricultural production involves the consumption not only of blue water but also of green water, which constitutes some 100% of plants' water intake for rain fed crops and a variable percentage for irrigated crops (Mekonnen & Hoekstra, 2011). The overall green water consumption for agricultural production in the Spanish Duero basin was estimated as 6672 Mm^3 in 2009 (MARM, 2011), and blue water consumption as 2650 Mm^3 (CHD, 2012). For 2015, blue water consumption by irrigated agriculture is expected to decrease due to efficiency improvements brought about by further improvement and implementation of modern irrigation systems, reducing the amount of water withdrawals from about 3770 Mm^3 in 2009 to 3291 Mm^3 (CHD, 2012). Assuming that rainfed agriculture remains stable, overall water withdrawals and consumption in the basin for a 2015 scenario are presented in table 4.3.

Livestock activity has a minor share of the region's economic value compared with other activities, with a 4.5% contribution to regional gross domestic product (GDP) (MAGRAMA, 2014). However, it has relative importance within national cattle stocks, accounting for 18% of the sheep population and 17% of the cow population, and providing over 14% of national milk production (CHD, 2012). Livestock water demands are mainly due to cattle drinking water requirements and maintenance of farm installations.

Aquaculture requires considerable amounts of blue water, as it constitutes the breeding ground for fish production. However, only some 3% of this water is consumed, with the other 97% periodically discharged back into the system. Food industry is the less intensive water user in the basin within the food production sector. It only accounts for 0.3% of water withdrawals and 0.03% of water consumption (CHD, 2012).

Table 4.2 presents the main accounting of water withdrawals and consumption entailed by food production in the Spanish Duero basin.

Activity	Water Withdrawal (Mm^3)	Water Consumption (Mm^3)
Agriculture	3,291	9,063*
Livestock	25	25
Food industry	13	3
Aquaculture	471	17
TOTAL	**3,800**	**9,108**

*Water consumption of agriculture in the basin was calculated as the sum of the total water footprint of crop production (green and blue water consumption) and the losses from the irrigation system through evaporation. Irrigation return flows are not considered as losses as they are returned to the system (Dumont et al., 2013).

Table 4.2. Water withdrawals and consumption associated with food production in the Spanish Duero basin. Source: Author's own elaboration from CHD (2012) and MARM (2011).

Here again there are important food-water quality trade-offs, as impacts on water quality generated by diffuse pollution from agriculture and livestock are intense and the main cause of groundwater degradation together with overexploitation (CHD, 2012).

Agriculture and livestock are the main sources of diffuse pollution, together with some sporadic accidental spills. The average annual pollution load accounts for 630 million kg, including nitrogen compounds (332 million kg), phosphorus (176 million kg) and potassium (122 million kg) (CHD, 2012). However, thanks to the spatial distribution of these loads and the dilution factor, the effects of diffuse pollution on surface water alone does not cause violation of water quality standards established in the legislation for these compounds (CHD, 2012).

In the case of groundwater, the extent of impacts is more intense. The main cause of pollution in groundwater is the leaching of nitrates and ammonia that infiltrate with drainage water into the groundwater system.

Waste water discharges from aquaculture are treated to a full extent, thus not causing any relevant impacts. Food industries in turn have a high pollution potential due to the production of highly polluted water effluents. The rate of industrial water discharges that do not receive adequate treatment in the basin is estimated at 12%, and their confluence is the cause of water quality problems in certain areas (CHD, 2012; CHD, 2014b). Figure 4.3 shows the location of aquaculture farms and food industries and the quality status of surface and groundwater according to the European Union Water Framework Directive standards.

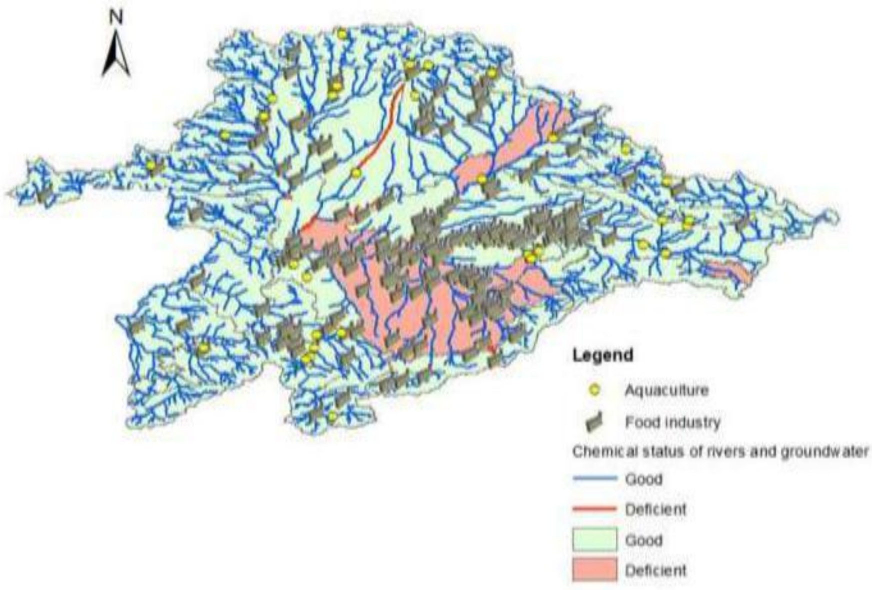


Fig. 4.3. Distribution of aquaculture and food industries in the Duero river basin and quality status of rivers and groundwater. Source: Mírame Duero Database.

4.3.3.3. Energy for water

The provision of water services, that is abstraction, transport and treatment, distribution, waste water collection and treatment, requires a considerable amount of energy, which plays an increasing role in the overall cost and economic viability of urban and rural water supply systems in the region. Energy consumption by the water supply cycle for the urban and industrial sectors (energy consumption of irrigation has been considered as an energy for food trade-off) in the region has been calculated for the purpose of this study, based on average unitary energy consumptions and flows for the different processes. Data for the flows in a 2015 scenario were obtained from the RBO (CHD, 2012); unitary energy consumptions were obtained from Hardy et al. (2012) and Ruiz (2014). According to these calculations, annual energy consumption by the urban-industrial water cycle in the Duero basin accounts for 690 GWh, which constitutes around 5% of the total electricity consumption in the region. Water abstraction, treatment to drinking quality standards and waste water treatment are the most energy intensive processes. Individual energy consumptions for the different stages are presented in Table 4.3.

Water cycle stage	Energy consumption (Gwh)
Surface water abstraction	226.5
Groundwater abstraction	34.8
Water treatment	100.25
Distribution	92.62
Collection and pumping	33.68
Waste water treatment	202.08
Reuse	0.02
TOTAL	**689.96**

Table 4.3. Energy consumption by the different stages of the urban-industrial water cycle for the Duero river basin. Own elaboration.

From all these water cycle stages, wastewater treatment is the most energy intensive and thus most problematic. In 2013, the rate of adequately treated urban waste water discharges only reached 54%

(CHD, 2014b). Though partly due to the poor state of the waste water treatment plant of one of the main cities (Ávila), the main reason for this low rate is the lack of treatment facilities in many small villages and rural areas. To date, several projects to install wastewater treatment plants for these communities have failed due to the high energy cost associated with the pumping and treatment processes (R. Huertas, personal communication). At present, the RBO is trying to find alternative solutions to this problem, which constitutes one of the main challenges to comply with the water quality objectives set by the EU Water Framework Directive.

4.3.3.4. Energy for food

Energy consumption by the food production sector is comprised by the energy required for agricultural production and the energy used by food industries. Food industry demand is estimated at some 20% of total industrial demand, with some 1,920 GWh/year (author's own estimations from data provided by Fenacore and Junta de CyL). Energy consumption by the agricultural sector (including agriculture and livestock activities) accounted for 10,800 GWh in 2007, about 12.65% of final energy consumption in the region. It is estimated that the agricultural sector can achieve energy savings of up to 78.3 MWh by 2012 as a result of the local *Energy Efficiency Plan 2008-2012* (Junta CyL, 2007). Irrigation comprises a 20% share of this demand, accounting for 2,350 GWh consumed in 2008. Energy demand for irrigation has increased considerably in the last decade as a result of the intense irrigation modernization process undertaken in the whole of Spain. In the case of the Spanish Duero basin, it has affected over 117,000 ha from 2006 and will reach some 130,000 by 2015 (MARM, 2010). Given the sharp rise of energy prices in the last several years since energy liberalization in late 2000, this higher dependency of agriculture on energy has resulted in an increase in the electric bill for farmers above 80% compared with 2005, making the cost of irrigation rise from 7% to 40% of total production costs (García Durango, 2014). This has caused energy to become a limiting factor for agricultural production within the region and in the rest of Spain. It has also resulted in waves of protests by farmer associations and individuals (García Durango, 2014; Agroinformación, 2014). This situation appears as a manifestation of conflicts brought about by the development of an agricultural policy from a water focused perspective, while overlooking the interrelations with energy and resulted in unexpected and undesirable consequences (Dumont et al, 2013) that only a coordinated WEF policy can help overcome.

4.3.3.5. Food for energy

The use of food products for energy production in the Spanish Duero basin is mainly done through the production of biofuels, as the main biomass plants in the basin use other type of input materials (straw, biogas from wastes and sludge, sanded wood dust and other wood materials and forestry waste products).

There are currently seven biofuel production plants in the region: four biodiesel plants and two bioethanol plants using food crops as prime matter and one biodiesel plant feed with forest biomass. In 2009 a total amount of 1,234,060 tons of seeds and grain from wheat, maize, barley, rape and sunflower were used to produce around 111,200 tons of biodiesel and 278,000 tons of bioethanol, using some 0.6% of cultivated land (author's own estimations from Junta CyL, 2009; Junta CyL, 2013 and data provided by Acor). Based on these estimations and objectives presented in the Regional Plan for Bioenergy of Castilla y

León[9] (Junta CyL, 2009) and data provided by local producers, the annual biofuel production by 2015 could reach 159,000 tons of biodiesel and 320,000 tons of ethanol, using around 1,500,000 of food material. As a result, land surface dedicated to grow crops for energy purposes will increase, reaching some 4.5% of irrigated land (22,500 ha) and 11% of rainfed land (286,000 ha) (Junta CyL, 2009).

As reflected in the Bioenergy Strategic Plan for Castilla y León (Junta CyL, 2009), there is an interest in developing bioenergy to enhance energy production and its economic value in the region, given the high potential to produce biomass from available resources and waste. Though part of this strategy relies on increasing the production of energy crops, and thus dedicating a higher part of arable land for this purpose, this is not expected to lead to competition with food production due to the existence of unused arable land (Junta CyL, 2013). Furthermore, within the regional context, this strategy aligns with the rural development policies intending to reactivate rural activity, seriously affected by a progressive abandonment and depopulation of rural lands. This process has been intensified in the last decades as a result of deruralization and migration to cities of the younger population, together with the low revenues provided by agriculture (Junta CyL, 2013). Hence, in this case, an example of synergistic relations and opportunities emerging from energy-food interrelations can be observed.

4.3.3.6. Overall water-energy-food nexus flows

After analysing the different arrows of the three axis triangle, the overall picture of WEF flows in the Duero basin is presented in table 4.4. These flows are calculated for a 2015 scenario in order to include the most recent planned energy projects and strategies.

	WATER	ENERGY	FOOD
WATER		WW[1]: 83,875 Mm^3 WC[2]: 280 Mm^3	WW[1]: 3,800 Mm^3 WC[2]: 9,800 Mm^3
ENERGY	690 Gwh		12,642 Gwh
FOOD		1,500,000 tons	

[1] WW: Water withdrawals

[2] WC: Water consumption

Table 4.4. Water-energy-food trade-offs by 2015.

In terms of water flows, table 4.4 shows that energy, mainly through the diversion of water for hydropower, generates five times more water withdrawals than food production, though the amount of water consumption is significantly lower. On the contrary, water consumption for food is almost three times higher than the amount of water withdrawn, due to the important role of the green water component in the growth of rainfed and irrigated crops, and 35 times higher than water consumption by energy. In this case, to understand the comparative impacts of energy and food production on downstream water availability, it is important to consider the timing of demands and the management of flows downstream of the dams to ensure water security. Dams for single hydropower use are subject to flow regulations according to the concessions issued by the RBO, ensuring than water requirements for downstream users and ecosystems are always met. Most multipurpose dams are operated by the state in coordination with

[9] Castilla y León is the main region within the Spanish Duero basin, accounting for 98.25% of its surface. Thus the basin's territory is under the auspices of regional legislation. See step 3 for further explanation.

the RBO, and downstream water flows are concealed with the needs for water for irrigation and urban supply during the dry season. Thus water withdrawals from hydropower do not constrain water availability in the basin, though they cause important impacts on the natural flow regimes of the river (Paredes et al, 2011). On the contrary, water consumed by agriculture is no longer available within the basin, thus limiting downstream water availability and groundwater recharge (Molden, 2007). This is an important aspect to consider by energy planners when developing their Strategic Plan for Bioenergy, where the design should be done in coordination with water allocation policies, to estimate the impacts in terms of additional water demands, timing and physical location (upstream or downstream) to assess its feasibility.

In terms of energy consumption, food production consumes 18 times more energy than the urban water cycle, with shares of 12.6% and 5% of total energy consumption in the region respectively. However, in both cases these demands are increasing, and the rising cost of electricity is leading to economic constraints.

4.3.2. Step 2: Analysis of the level of integration and coordination of sectorial policies and institutions

To date, water, energy and agricultural policies in the Duero basin have been developed and implemented independently. These policies are made at different scales, since water planning is made at the basin scale, while energy and food planning are mainly undertaken at the national scale, though subject to further development by regional authorities. This distribution of competences, in both the legal and implementation aspects, together with the lack of internal communication, have led to several conflicts between administrations and made sectorial management policies difficult to coordinate. As a result, the existence of inconsistencies and inefficiencies amongst policies, as well as the emergence of unexpected outcomes, has been frequently observed in the last decade. An example is the case of the rebound effect on water and energy use due to the agricultural modernization policy mentioned above.

In terms of regulation and planning, although coordination and inclusion of crossed-sectorial aspects have not been traditionally present, some steps have been taken. An example within the water sector is the inclusion of a chapter looking at the interactions with other policies regulating crosscutting aspects, including energy policy, within the new Hydrologic Plan in the Water Framework Directive. However, the analysis identifying overlapping objectives still needs to be translated into real communication and joint actions between the management institutions involved.

Within the energy sector, most of the cross-cutting regulation considered in the National Energy Plan (MINETUR, 2011) is related to climate change and atmospheric emissions, while no water regulations are included. However, among the environmental variables considered by the energy planning models, some water related variables are included, though only covering water availability aspects and mainly as a conditioner for hydropower production. In terms of the sustainability indicators of energy policy considered in the plan, there are five indicators related to water issues: cooling water volume, crosscuts between energy infrastructure and the water system network, occupation of Public Hydraulic Domain areas, occupation of Public Coastal Domain areas and fishing areas and occupation of areas at flood risk (MINETUR, 2011). However, impacts on water quality are not included at any stage. With respect to other parallel energy strategic plans, the Renewable Energy Plan (IDAE, 2011) tackles the water issue through the call for innovation and application of water efficient technologies for Concentrated Solar Power (CSP) facilities, which account for the highest unitary water withdrawal rates among renewable energies.

In summary, the analysis shows that both water and energy planning are increasingly taking both resources into account to some extent when developing their future roadmaps. However, this is still done by each institution individually, without any coordination or interaction to build joint initiatives, and is not effectively translated into practice in the implementation and monitoring of these policies.

4.3.3. Step 3: Discussion on existing and potential strategies for conflict mitigation and identification of solutions

As illustrated in previous sections, the lack of coordination and communication between sectorial institutions when designing and implementing water, energy and food policies has led to several conflicts, crossed efficiencies and unintended outcomes. However, some initiatives have been started, especially by the RBO, to find integrated solutions for better accounting practices and managing trade-offs.

The analysis shows that food production is the most important water consumer, the main cause of groundwater degradation problems and has become increasingly dependent on energy for irrigation, thus limited by rising energy costs (Table 4.4). To tackle these problems the RBO is promoting the creation of groundwater users' Associations (CUAS in Spanish). The grouping of farmers into this type of user groups is a common practice in Spain, which allows a better and more controlled management of water use and provides several benefits for farmers (Rica et al., 2012). Some of these benefits are the development of strategies to reduce or share pumping energy costs and look for alternative solutions to acquire irrigation water. The RBO is promoting this practice by the organization of workshops to inform farmers about the benefits and options and offering facilities and help for administrative arrangements.

Another initiative of the RBO is the organization of 'Schools for mayors', where mayors from different villages are invited to thematic workshops where they are informed about relevant water ecosystems' sustainability issues and concerns. Some of the more recent concerns are related to the possible development of hydraulic fracturing activities in certain parts of the region, an activity where the water-energy interconnections are evident. The lack of reliable and objective accessible information about the fundamentals of this technique and the real risks it can entail is causing social concern and protest movements among the population. Local authorities are confused and need to find reliable objective and sound technical criteria on which to base their decisions. This type of initiative, together with the creation of a knowledge platform in Spanish could be very useful to educate the population and local authorities about this topic. Doing so in an objective but informal way will reduce social tension and promote informed decision making. This will also be especially important for the RBO to make water allocation decisions if hydraulic fracturing develops in the region, especially during the production phases where water requirements are concentrated in very specific and short periods of time (Puls, 2013).

A third initiative undertaken by the RBO was the recent review and update of all hydropower concessions in the basin to ensure their compliance with the legislation, particularly in the aspects of minimum ecological flow releases and the installation of functional fish passes. This has reduced the impacts of hydropower on river connectivity and aquatic ecosystems integrity (Huertas, 2014; CHD, 2011).

To address the problem of waste water treatment in rural communities and small villages, where the high energy cost was the main limiting factor for the development of conventional treatment plants, the RBO is exploring alternative waste water treatment systems that do not require pumping and minimize energy use (CHD, 2013b). Within this project, different options are tested for a series of pilot villages, depending on their particular characteristics, to find the most suitable and economically viable treatment alternative. Some of the alternatives include septic ponds, constructed wetlands, Imhoff tanks, sand filters and anaerobic fixed beds.

In addition to these existing initiatives, we suggest two possible measures that could help identify existing and possible conflicts among policies, and then develop prevention or mitigation strategies. First, as an essential element for integrated resource management (Jønch-Clausen et Fungl, 2001), public participation should be involved in energy planning, as it is currently in water management planning. The elaboration of Hydrologic Planning at both national and river basin levels includes a step where all the documents are made public for consultation and discussion. This step is in contrast to the existing energy planning process, where energy plans are only submitted for approval to government (both the executive and legislative commission) (Ruiz de Apodaca, 2010). This would allow stakeholders to air existing issues and conflicts derived from nexus trade-offs to be considered by energy planners, who may not be able to detect them from a strategic energy-oriented position.

Second, the numbers of energy for food and water and related conflicts identified in the analysis suggest that a thoughtful evaluation of the 'energy footprint' of irrigation modernization and additional examination of energy trade-offs on water availability need to be included in the next Water Planning period (2015-21). There is still a need for a precise ex-post assessment of the potential increase on energy use and the subsequent cost entailed by the modernization process of irrigation in the Duero Basin. In the 'Identification of important topics and challenges' section of the 2015 Hydrological Planning Revision Phase, modernization is again presented as the best solution to reduce agricultural water use and face the new demands expected for the next period 2015-2021 (CHD, 2013a). However, the increasing cost of the electricity bill is still not reflected among the possible side consequences of the measure, while it constitutes the main concern for farmers. To avoid conflicts and future constraints to the economic sustainability of irrigated agriculture, the capacity of farmers to cope with energy costs during the exploitation phase should be a primary aspect to consider when evaluating the viability of new modernization projects. Meanwhile, possible solutions have to be explored for already implemented projects where farmers have serious economic constraints. It is an issue in several regions in Spain and there is an intense debate among farmers, electricity companies and public administration on how to find win-win solutions. Some of the debated solutions include economic help for farmers, elimination of the fixed electricity tariff during the non-production seasons, irrigation during the off-peak hours when electricity is cheaper, pipelines maximizing the use of gravity and natural slopes when possible (del Campo, 2014).

4.4. Conclusions: the way forward

As discussed in this chapter, the WEF Nexus can be considered as a framework that helps connect, coordinate and reinforce individual water, energy and food management policies by paying special attention to the identification, understanding and characterization of interconnections and trade-offs, in order to build aligned and coherent strategies/actions that permit synergies. This should be applicable both within the political sphere, at either national, regional or local scales; and at a business or even household scale, where resource management and optimization is also required.

In general terms, it is only recently that the extent and importance of the WEF nexus problem and the need to go deeply into the understanding of trade-offs and their possible side effects from a policy perspective have been realized. In the case of the Duero basin, to date water and energy policies have been roughly considered together when planning, though there is still a lack of interconnection between management institutions.

Some of the main challenges derived from WEF trade-offs for the RBO to deal with include ways to balance energy prices to allow farmers face irrigation energy costs, less energy costly waste water treatment solutions for small villages, safeguarding the integrity or rivers segmented by hydropower and the creation of social awareness. These kind of conflicts and unexpected and unintended consequences will hopefully be prevented in the future if sufficient attention to the underlying connections is made. Meanwhile, prevention and coping strategies need to be developed beforehand to ensure resilience in case of large fluctuations of key energy, food or water security variables, something that seems to be fairly likely to happen in the future. In this sense, there has been an active participation and involvement of both the Duero Basin Organisation and the Spanish government within the 2014 national and international water-energy nexus debate (UN Water, 2014a; Water Energy Exchange Global, 2014). This suggests that the message of the importance of understanding the interlinkages and coupling policy strategies is gradually being adopted, and new policy measures and coordination strategies could be expected.

CHAPTER 5

WATER-ENERGY NEXUS: BRINGING PERSPECTIVE OVER THE ROLE OF LARGE AND SMALL SCALE HYDROPOWER IN THE DUERO

Chapter 5. Water-energy nexus: Bringing perspective over the role of large and small scale hydropower in the Duero Basin in Spain

5.1. Introduction

With situations of water scarcity getting more accute and spread out over the planet, climate change and energy demand prospects pointing at a 40% increase by 2040 (IEA, 2014), hydropower has been increasingly seen as a two-fold solution: first it provides renewable, low carbon and endogenous energy and second it increases water storage capacity. Several scenarios predict an increase in storage capacity equivalent to 3,600 km^3, that is 40% of current capacity, will be needed to reach the water and energy goals by 2030 (Berga, 2015). After a golden age during the 40s, 50s and 60s, when hydropower was considered the revelation of clean energies, a series of large scale hydropower projects (LHP) were developed worldwide. However since then the range of associated environmental and social impacts have become increasingly evident, marking the start of a wide debate over its virtuosity (Abbasi & Abbasi, 2011). More recently, a countertrend towards small scale hydropower (SHP) projects has emerged, praising its virtue to provide similar benefits than bigger infrastructures but with reduced impacts due to the smaller size, land and infrastructure requirements. This new panacea has prompted both emerging economies with high untapped hydropower potential and countries with limited capacity to increase the use of hydropower to go for the deployment of a mosaic of SHP projects along river basins and subbasins. Examples can be found in China, India and Brazil (Chen & Li, 2001; Naidu, 1996; White, 2008) as well as in Norway and Spain (Bakken et al., 2012; Morán-Tejeda et al., 2012).

However, several studies have raised concerns over the cumulative impacts posed by a large deployment of small hydropower projects cascading along a river (Xiaocheng et al., 2008; Thoradeniya et al., 2007), which can match or even outweigh those of large hydropower projects that provide an equivalent energy output (Abbasi & Abbasi, 2011; Bakken et al., 2012; Kibler & Tullos, 2013; Skinner & Lawrence, 2014). This has opened the debate to discussions and different opinions whether first, hydropower should be further promoted and second, if so, which type of development would be preferred when considering environmental externalities and short and longterm economic sustainability (Aggidis et al., 2010; Ansar et al., et al., 2014). Within this arena of contradictory arguments, ranging from a continued promotion of multipurpose dams as an essential element to face future water and energy challenges (Berga, 2015; Branche, 2015) versus strong opposition due to environmental and social concerns, governments face difficult decisions to balance the pros and cons. where more evidence based studies are needed to help guide decision making.

In the European context, SHP accounts for 13,000 MW of installed capacity, with Europe the second biggest user behind Asia (Arcadis, 2011). Predictions of growth in SHP according to the National Renewable Energy Action Plan (NREAP) indicate a 11% increase in energy production and 38% increase in installed capacity from 2005 to 2020. For the same period the electricity generation from LHP stations is expected to increase by 5% while an additional capacity of 16% will be installed (Arcadis, 2011).

In the particular case of Spain, this issue is gaining attention and special relevance since reservoirs are one of the star pieces argued to play a main role in water, food and energy security: i.e. for hydroelectricity and irrigation. In Spain, a strong pro-dams policy was implemented during the second half of the 20th century, leading to the construction of more than 1,300 dams, with an enhancement in surface supply capacity from 9% in natural regime to 38% and with a total water storage capacity of around 53,000 hm^3 (Martínez-Cortina, 2009; Hardy & Garrido, 2010). At present, surface water represents around 62% of total water use (Hardy & Garrido, 2010), from which up to 50% goes to irrigated agriculture (López-Gunn et al., 2012a), the main water consumer with a share of 68% of total water use. However, the exponential rise in installed capacity from 1960 onwards, with huge upfront associated investments, has however not led to the expected parallel increase on e annual producible hydroelectric power – and consequently nor on annual energy production. According to Gómez (2009), this is due to the increased limitations and competition over the water resources available as shown in Figure 5.1. It should be noted that in Figure 5.1 the producible energy expressed in GWh is obtained from using the maximum installed capacity from the whole series. All this development included both LHP and SHP projects.

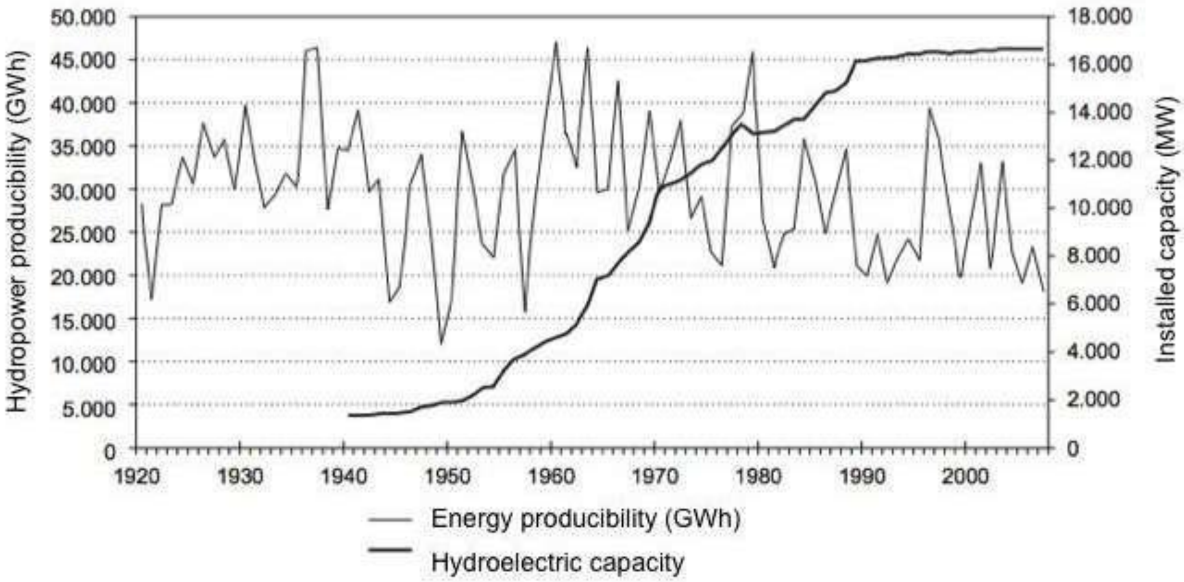


Fig. 5.1. Evolution of hydropower installed capacity vs energy producibility in Spain. Source: adapted from Gómez (2009)

Global numbers in terms of energy production and water storage for hydropower performance have been made by energy and water planning at the national and basin scales. However, there are few if any assessments of the cumulative effects on water and energy security and the environmental impacts of each type of hydropower development within each basin.

This study aims to fill one of these knowledge gaps by analysing the differential contributions of large and small scale hydropower in the Duero basin, the largest transboundary basin in the Iberian peninsula, to regional water and energy security. It also aims to compare the cumulative impacts of each type of development on the river system and surrounding ecosystems, and provide a reflection on potential improvements to reduce the impacts and enhance the value and future resilience of the hydropower scheme.

5.2. Methodology

5.2.1. Study system description

The Duero Basin is the largest transboundary system in the Iberian Peninsula, covering an area of 98,073 km^2 (de Miguel et al., 2012). The main river in length, the Duero is born in the Iberian Mountains and ends in Porto at the Atlantic Ocean, running through 770 km in Spain and 143 in Portugal (CHD, 2012). At its birth, the Duero river flows through the sedimentary, metamorphic and plutonic materials of the Iberian and Central Mountains, to later cross a wide Cenozoic basin formed by terrigenous and evaporite deposits from the Tertiary and Quaternary periods, with depth over 2,000 m and holding an important aquifer. The main tributaries feeding it come from the Cantabric and Leon Mountains to flow into its right bank. On its way down to the Portuguese frontier, the Duero river forms the Arribes canyon along a stretch of 100 km. This study will focus on the Spanish part of the basin, which accounts for 80% of its surface (78,859 km^2) and a population of 2,200,000 inhabitants (CHD, 2012). The Spanish part of the basin partially encompasses eight provinces, although 98% of its surface and population in the Castilla Leon region as shown in Figure 5.2.

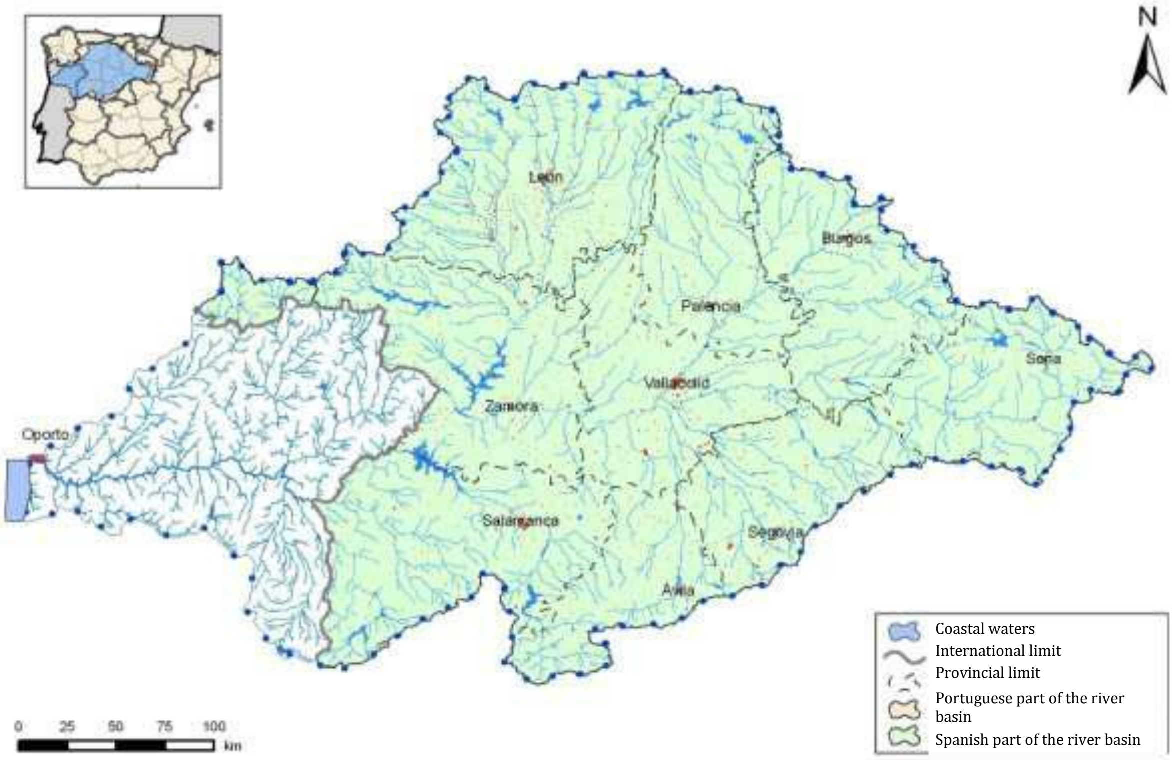


Fig. 5.2. Location of the Duero River Basin in the Iberian Peninsula. Source: OPH-CHD

The Spanish Duero basin has a continental Mediterranean climate with average precipitation of 625 mm/year resulting in 13,600 Mm^3 of available water. It has a characteristic erratic inter-annual and intra-annual precipitation variability in time and space, due to a changing climate with typical Mediterranean summer drought alternated with cold and hot Atlantic fronts leaving intense precipitation and flooding episodes (CHD, 2014c). These characteristic and long-standing summer droughts were the drivers for the creation of the single use dams for irrigation purposes.

The catchment is formed by a dendritic drainage network of 83,200 km with 13,530 km considered as water bodies for the purposes of the EU Water Framework Directive. Especially relevant amongst its numerous tributaries are the Pisuerga river – which runs through the Cantabric and Iberian Mountains -, and the Esla river – closer to the Portuguese frontier and providing the greatest flow contributions to the basin (CHD, 2014c). The Spanish part of the Duero river has 75 main reservoirs associated to important dams, and a great number of small reservoirs associated to minor dams or irrigation diversion structures. 18 of these 75 main reservoirs are owned and operated by the state for several purposes (river flow regulation, water supply, recreation) and 40 are used for hydropower generation, either solely or jointly with other purposes like i.e. irrigation or recreation.

The total consumptive [10] water demand in the basin is 4,529 hm^3 (CHD, 2014c). Agriculture and hydropower production are the most important water users, concentrating over 85% of consumptive water demand and over 90% of non consumptive water demand respectively. The basin plays an important role in national energy and food production, with hydropower supplying almost 25% of the national energy demand and local agricultural production of grain reaching 24% of the national total (CHD, 2012). However, such demands have led to competition for water resources, particularly in dry periods, as well as the problem of drastic natural flow regime variation and accompanying ecosystems degradation. This has resulted in stricter regulations for the maintenance of minimum ecological flows (Morán-Tejeda et al., 2012; Paredes et al., 2011).

In terms of ecosystems, the basin holds considerable ecological richness with 97 areas declared as Sites of Community Interest (SIC) under the Habitat Directive - with 86 of these water related –, and a network of 54 Special Protection Areas under the Birds Directive (CHD, 2014c).

5.2.2. Study design and data collection

The Spanish part of the Duero basin accounts for 164 hydropower stations with installed capacities ranging from 8 to 855 MW (CHD, 2011). In the case of Spain, and of most European countries, the distinction between high scale and small scale hydropower is built upon the installed capacity, taking a threshold of 10 MW as the inflexion point. Despite the adoption of the installed capacity as the standard to differentiate between LHP and SHP being quite generalized, there is not a consensual definition of large and small scale hydropower, nor of the threshold to separate them (Kibler & Tullos, 2013; IPCC, 2011; ESHA, 2009). The limits for 'small scale' are generally set to 10 MW in Europe (Abbasi & Abbasi, 2011), 25 MW in the United States and up to 50 MW in China (Kibler & Tullos, 2013). For this study, the European and Spanish definition of large scale hydropower installed capacities above 10 MW and small scale hydropower as capacities below 10 MW will be adopted. However the rationality and appropriateness of using the installed capacity as the standard to differentiate between both technologies will be further analyzed in the discussion section of the chapter.

In 2011 the Duero River Basin Agency carried out a revision and updated all hydropower concessions, their production characteristics and their compliance with certain environmental standards - such as the presence of fish passes or the compliance with minimum environmental flows - through a series of field

[10] Consumptive use of water is defined as 'water use that permanently withdraws water from its source; water that is no longer available because it has evaporated, been transpired by plants, incorporated into products or crops, consumed by people or livestock, or otherwise removed from the immediate water environment' (Vickers, 2001).

visits and on-site data collection. The outcomes of the revision were compiled in a General Report (CHD, 2011) and a set of fact sheets with the information of each particular hydropower project, which have served as the main source of information and data for this study. According to this information, there are currently 23 large scale and 141 small scale hydropower plants operating in the Spanish part of the Duero basin. The 164 plants sum up an installed capacity of 3,923.42 MW. Of the 164, 122 are Run-of-River[11] (RoR) plants and 42 are Reservoir Hydropower[12] (RHP) plants - associated to big dams and reservoirs - from which 27 are state owned and operated. Amongst the RoR plants, 118 have their diversion point associated to a small dam with average heights between 5 and 10 meters, 12 benefit from a waterfall created by a canal and 1 uses emerging water from a water spring. Figure 5.3 shows the distribution of small and large scale hydropower plants along the basin. In addition, a list of all large and small scale hydropower plants considered for the study, their main characteristics and values for the study indicators is provided in annex 8.

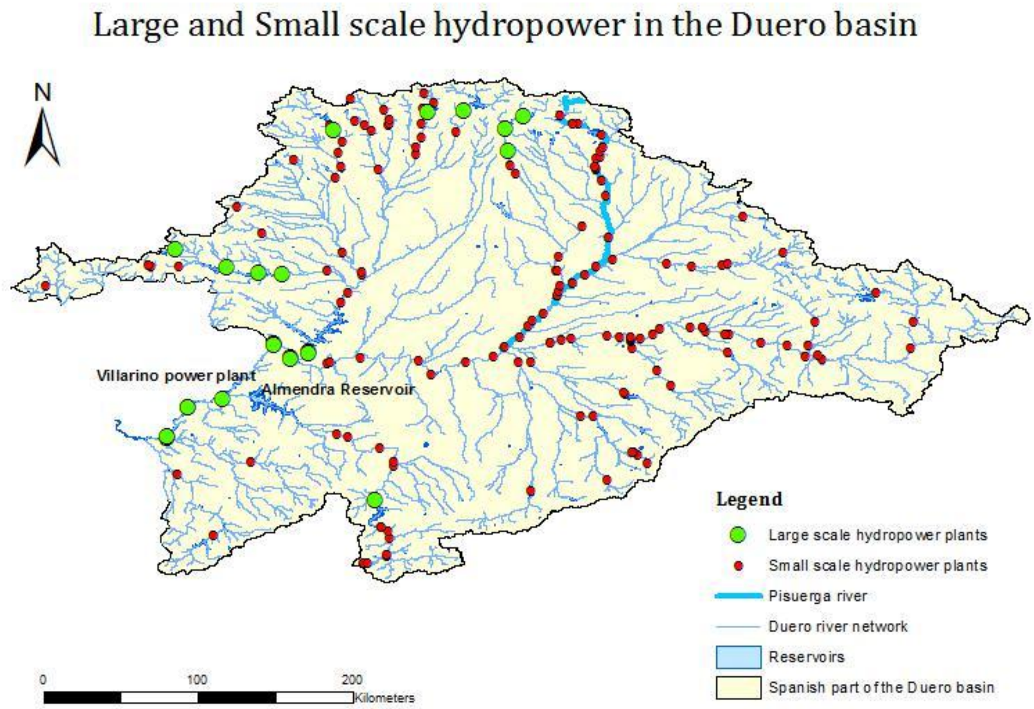


Fig. 5.3. Distribution of large scale and small scale hydropower plants in the Spanish part of the Duero Basin

The analysis presented in this study has the aim to evaluate the cumulative contributions of LHP and SHP to regional water and energy security, as well as certain cumulative impacts on the basin hydrology and natural environment. With this purpose, a set of indicators has been developed and is presented in table 5.1. Water and energy security indicators have been selected on the basis of existing conceptualizations of these two aspects. The selection of impact categories and indicators has been based upon literature review and adapted to data availability.

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11 Run-of-River (RoR) plant: plant harnesses energy for electricity production mainly from the available flow of the river (IEA, 2012).

12 Reservoir Hydropower (RHP) plant: plants associated to artificial reservoirs created by building a dam to control the natural river flow (IEA, 2012).

Impact Category	Component	Indicator		Unit	Source
Contributions to energy security	*Resource availability*	Number of power stations		Number	Authors' own
		Installed capacity		MW	EIA, 2013
		Annual power generation		GWh/year	EIA, 2013
		Security of supply	Regulated capacity	%	IDAE, 2011
			Reversible capacity	%	IDAE, 2011
	Affordability	Normalized energy cost		c€/kWh	IDAE, 2011
	Efficiency	Energy demand covering capacity		%	Authors' own
Contribution to water security	*Water access and supply*	Water storage capacity		hm^3	UN Water, 2014b
		Water demand covering capacity		%	Author's owned
	Irrigation supply	Hydropower plants connected to infrastructure providing irrigation services		%	IHA, 2003; IEA, 2012
		Water storage capacity of dams with energy-irrigation purposes		hm^3	ICOLD, 2015; Shiferaw et al., 2005
	Environmental flows	Hydropower plants not meeting environmental flows		%	Morán-Tejeda et al., 2012; Paredes et al., 2011
	Flood risk reduction	Hydropower plants enabling flood regulation		%	IEA, 2012; IPCC, 2011
Environmental impacts	*Flow regime*	Water withdrawal		hm^3	CHD, 2012
		Water consumption		hm^3	Herath et al., 2011; Mekonnen & Hoekstra, 2011
		Length of river with disturbed natural flows		km	Bunn & Athington, 2002; Kibler & Tullos, 2013
	Connectivity	Number of dams or obstacles		number	Kibler & Tullos, 2013
		Percentage of scalable dams		%	ESHA, 2009; Arcadis, 2011
	Habitat loss	Reservoir surface area		ha	Kibler & Tullos, 2013

Table 5.1. Aspects and indicators considered in the study

Impact Category 1. Contribution to energy security

Energy security has been defined and characterized in many different ways and multiple indicators have been proposed for its assessment. In general, the concept of 'energy security' is applied to a region or country to refer to the vulnerability of energy supply to economic, geopolitical, environmental and performance factors (Brown et al., 2011; Kruyt et al., 2009). There is an international debate on the conceptualization of the different dimensions integrating energy security. Different categorizations have been proposed by several authors and institutions (APERC, 2007; Kruyt et al., 2009; Sovacool & Brown, 2010; Löschel et al., 2010), which mostly present a common base (availability, economic and stewardship aspects) with slight variations depending on the additional external factors included (social, climate change, health, geopolitical, among others). In this study, the conceptualization made by Sovacool & Brown (2010) will be considered and adapted for its application at the regional-river basin scale. These authors define energy security as being composed of four dimensions: resource availability (independence, diversification and continuity of supply), affordability (affordable prices, stability of prices, and quality of supply), efficiency (production costs and demand behaviour and practices) and environmental stewardship (control of environmental externalities and shift towards renewables). The differential cumulative contributions to these dimensions of currently operating LHP and SHP in the basin will be assessed through the following indicators:

Resource availability is evaluated considering the existing potential for energy production, continuity of supply and diversification. Provided that the focus is put on two particular energy sources and not on the full mix, the diversification aspect will be assessed in terms of physical or spatial diversification of production. Meanwhile, it is assumed that the contribution to independence of both sources is equal, as both are endogenous energy sources using local resources. The indicators chosen for this category are the following:

- *Number of power plants (number):* the number of power plants distributed along the basin reflects the level of physical diversification of production.
- *Installed capacity (MW):* indicates the cumulative installed capacity for operating small and large scale hydropower plants in MW. The installed capacity for power plants refers to the maximum electric output that the generator can produce and is usually measured in Wats (W) or its multiples (kW, MW. GW) (EIA, 2013). Data were obtained from the Duero River Basin Revision Report (CHD, 2011).
- *Annual power generation (GWh/year):* the annual power generation is the cumulative amount of power produced over a year. It is usually expressed in GWh/year and calculated as a product of the installed capacity and the number of operating hours (EIA, 2013). For the purpose of this study, data from empirical estimations were preferred to theoretical production values when available to get more accurate cumulative estimations. Data were obtained from the Duero River Basin Revision Report (CHD, 2011).
- *Contribution to security of supply:* it will be assessed through the estimation of the installed capacity that enables to control energy production and adapt it to demand fluctuations, thus providing stability of supply (IDAE, 2011).
- *Regulated capacity (%):* is expressed as the percentage of total installed capacity that enables to control the timing of energy production, mainly through the presence of a dam with regulation capacity (IDAE, 2011).
- *Reversible capacity* (%): represents the percentage of installed capacity with coupled pumping or reversible systems. These systems do not only enable to control the timing of energy production, but also help to offset production peaks generated by other energy sources while restoring water reserves in the upper part of the dam (IDAE, 2011).

Affordability: given that hydropower energy production does not directly depend on the use of – often imported- fuels and thus on their price, it is assumed that the main technology driven factor influencing the final price of electricity production for the case of hydropower is the cost of energy production (EIA, 2014). Meanwhile, the quality of energy provided - access to electricity, fuels or primary biomass as defined by Sovacool & Brown (2010) – is assumed to be equal since in both cases the final output is electricity that is injected into the grid and cannot be distinguished from electricity coming from other energy sources. Affordability is assessed through the following indicator:

- *Normalized energy cost (c€/kWh):* average normalized energy costs for power stations below 10 MW and above 25 MW (IDAE, 2011). Data for Spain were obtained from IDAE (2011).

Efficiency: the efficiency of energy supply will be assessed through the capacity to cover existing energy demand in the region. Impacts related to demand behaviour are not considered, since the assessment refers to the supply side.

- *Energy demand covering capacity (%):* this indicator represents the percentage of regional energy demand that is covered by each type of hydropower production. It is obtained as a fraction between total annual energy production and regional energy demand. Data for regional energy demand were approximated to the Castilla and León region, which occupies 98% of the territory of the basin. This indicator has been defined at a regional scale to keep scale coherence within the study and provide a perspective for the region. However, it should be noted that Spain has an integrated energy system that is regulated and managed at national scale.

Environmental stewardship: the environmental stewardship is assessed in the section of *environmental impacts*, where the cumulative extent of the impacts from each type of technological development on certain variables is estimated. The environmental stewardship - impact dimension has been presented separately since it influences and is influenced both by energy and water security.

Impact Category 2. Contribution to water security

Water security, like in the case of energy security, has been conceptualized in many different ways. Lautze & Manthrithilake (2012) proposed an indicator to evaluate water security through five components: water availability to meet household demand, water availability for food production, conservation of environmental flows, risk management and independence. Like in the case of energy security, the independence factor is considered equal for both types of hydropower developments. The differential contributions of large and small scale hydropower to the rest of the components will be assessed through the following indicators.

Water access and supply

- *Water storage capacity (hm^3):* water storage in dams is an indicator of available supply for human needs (UN Water, 2014b). This indicator will show the amount of water stored in dams associated to hydropower plants.
- *Water demand covering capacity (%):* expressed as the ratio between water supply provided by hydropower dams and total water demand, this indicator will show the contribution of hydropower dams to meet regional water demands.

Irrigation supply

- *Hydropower plants connected to infrastructure providing irrigation services (%):* Hydropower plants can contribute to irrigation water supply when they entail the construction or contribute to the maintenance of associated infrastructures that also provide water for irrigation (IHA, 2003; IEA, 2012). This indicator reflects the percentage of hydropower plants with associated infrastructures, including multipurpose dams, canals and small ponds that are also currently used for providing water for irrigation in the basin.
- *Water storage capacity of dams with energy-irrigation purposes (hm^3):* the existence of dams has traditionally contributed to ensure water availability for human supply and irrigation in periods of scarce rainfall and river flow declines (ICOLD, 2015). Based on this statement, a variation of the

water storage capacity indicator (Shiferaw et al., 2005) to show water storage capacity in dams with irrigation purposes is an indicator showing water availability for irrigation supply procured by dams with shared energy-irrigation purposes.

Environmental flows

- *Hydropower plants not meeting environmental flows (%):* hydropower plants can threaten the maintenance of environmental flows if the amount of flow released downstream of the dam or left in the stretch between the diversion and the restitution points do not meet the minimum ecological requirements (Morán-Tejeda et al., 2012; Paredes et al., 2011). The Spanish Water Plan defines ecological flows as 'the minimum flow to allow a sustainable maintenance of the functionality and structure of aquatic ecosystems and related terrestrial ecosystems, helping to achieve the good ecological status of rivers' (CHD, 2012). The proposed indicator shows the percentage of hydropower plants where insufficient flows were identified in certain periods of the year and a special regime of environmental flows had to be applied, as reflected by the assessment performed for the last review of the Duero Water Plan (CHD, 2014c). It reflects the relative contribution of each type of hydropower development to disturbed environmental flows in the basin where additional regulation and management measures are required.

Flood risk reduction

- *Hydropower plants enabling flood regulation (%):* dams with regulation capacity have a positive effect to reduce the risk of extreme floods (IEA, 2012; IPCC, 2011). This is true for severe floods that can cause important economic and human losses, and is the effect that will be considered in this analysis as part of the water security function. The cumulative contribution of small and large scale hydropower capacity to flood risk mitigation will be assessed as the percentage of hydropower plants associated to dams with flood regulation functions. Data were obtained from the last update of the Duero Water Plan (CHD, 2014c).

It should be noted though that dams also have the effect of stopping periodic regular floods which have important functions like river morphology and flood plain configuration, spatial heterogeneity - a basis for biodiversity -, aquifer recharge and natural fertilization of the alluvial soil. This effect has allowed humans to settle in emplacements next to rivers where it was not possible before, but has also entailed negative consequences for the river ecosystem and increased the risk of flooding for those communities (Richter & Thomas, 2007).

Impact Category 3. Environmental impacts

Hydropower plants have several environmental impacts, including impacts on river hydrologic variables, water quality, aquatic and surrounding ecosystems, land occupation and emissions to the atmosphere (IEA, 2012; IPCC, 2011; Arcadis, 2011). The selection of impact categories for this study has been strongly influenced by the availability of data, time and resources, and oriented towards river hydrology and ecosystems. However, the authors acknowledge the importance of other categories like greenhouse gas emissions or water pollution, and suggest the evaluation of these impacts in further studies.

This assessment will focus on the cumulative impacts on river flows and water balance, riverine protected habitats, river connectivity and aquatic ecosystems, through the following indicators:

Flow regime

- *Water withdrawal (hm^3):* refers to the total water flow withdrawn and turbined on a yearly basis (CHD, 2012). Water withdrawal over a year is estimated using the following equation:

  $WW = Q_I * h$

  where Q_I is the mean input flow coming into the turbines (m^3/h) and *h* is the number of operating hours per year.
- *Water consumption (hm^3):* consumptive water use accounts for evaporation losses from the surface of artificial reservoirs that feed hydropower plants (Herath et al., 2011; Mekonnen & Hoekstra, 2011). Although the authors acknowledge that for an accurate assessment of the water footprint of reservoirs a more complex indicator would be preferred (Herath et al., 2011; IEA, 2012), for the purpose and conditions of this study, this method was regarded as the most suitable. Due to data limitations, only evaporation from reservoirs over 0.5 hm^3 has been considered. Evaporation from smaller reservoirs or river enlargements caused by small dams can be considered negligible according to the Duero Water Plan estimations (CHD, 2012).
- *Length of river with disturbed natural flows (km):* the retention of water in dams and its diversion into lateral channels impact the natural river flow conditions (Bunn & Athington, 2002; Kibler & Tullos, 2013). This indicator estimates the cumulative length of river stretches with modified natural river flow conditions, as a result of lateral diversion or the presence of dams. It is obtained as a sum of the distances between the catchment and the release points for each hydropower project. In the case of hydropower plants associated to a dam, the length of river occupied by the reservoir is also included. Distances were measured on aerial photographs, using geographical coordinates of the catchment and release points from CHD (2011).

Connectivity

- *Number of dams (number):* the presence of dams slows down natural river flow velocity, retains transported sediments and causes disturbances to water temperatures (ESHA, 2009; Arcadis, 2011), thus disturbing upstream-downstream connectivity. This indicator shows the number of dams - either big dams leading to water storage in reservoirs or small dams for water diversion - associated to hydropower plants as an indicator of cumulative river segmentation.
- *Percentage of non scalable dams (%):* dams can constrain habitat connectivity (Ward et al., 1999; Bakken et al., 2012; Kibler & Tullos, 2013), while hindering migration of certain fish species (Northcote, 1998). The number of dams not including effective fish ladders is used as an indicator of cumulative segmentation and barriers to fish migration. Although due to data availability only limitations to the effects on fish have been considered. It should be noticed however that the river biota is composed of a much more complex network of organisms that are affected by river connectivity disturbances.

Habitat loss

- *Reservoir surface area (ha)*: The creation and filling up of a reservoir involves the occupation of land and the transformation of original habitats (Oliver, 1974; Lewke & Buss, 1977), which in the case of big reservoirs can affect hundreds of hectares of native ecosystems. To assess this impact the cumulative surface occupied by reservoirs associated to each type of hydropower plants is used as an indicator of habitat loss (Kibler & Tullos, 2013).

For water security and impact indicators an absolute and relative value is provided, except for those expressed as a percentage which is a relative value in itself. The absolute value presents the sum of the individual values from the different plants integrating each type of hydropower development and provides the macro-perspective. The relative value expresses the normalized values per kWh, enabling a balanced comparison based on a same reference unit (Kibler & Tullos, 2013).

Initially an additional impact category to assess the *disturbance effect of hydropower projects on conservation areas* was to be included, based on the premise that dams and water flow disturbances may indirectly influence off-site habitats and thus cause negative effects on nearby protected areas (Kibler & Tullos, 2013; Zhao et al., 2012). It seemed a relevant aspect since the Duero basin has remarkable ecological value, with around 16.3% of its surface designated as Sites of Community Interest (SIC) by the Habitats Directive and 18.35% as Special Protected Areas (SPA) by the Birds Directive, summing a total of 23.06% of the surface holding some kind of protected legal status considering the overlaps (CHD, 2014c). Moreover, it was found that 70% of LHP and 52% of SHP were located within these areas. However, it was also noticed that most of these SIC were created to protect riverine vegetation formations that had developed after, as result of the installation of the dams and the reduction of river flows downstream, which allowed vegetation to expand and colonize the flood plain. Meanwhile, the high number of reservoirs and lentic ecosystems resulting from the installation of the dams also attracted a number of bird species, especially from the mallard group, which motivated their declaration as SPAs.
This brought the debate of 'who was first' to the table, and the assessment of the potential disturbance by hydropower projects of natural sites that had artificially emerged as a consequence of their installation seemed paradoxical. It was thus decided not to include this impact category in the study. Nevertheless, the authors found it relevant to include a brief discussion to this peculiar case since it may probably be the case for other European basins, to highlight the common overvaluation of certain ecosystems – sometimes as a result of poorly understood actions, fashions or conservation currents – to the detriment of the original though maybe less 'idyllic' habitats.

The data for the indicators were obtained from several sources, including databases and materials provided by the Duero River Basin Authority, Duero River Basin Management Plan, GIS data and publicly available studies.

5.3 Results

The results from the assessment are presented in table 5.2.

Indicator		Macro hydropower (LHP)		Micro hydropower (SHP)	
Contributions to energy security					
Resource availability	Number of power stations	23		140	
	Installed capacity (MW)	3,729.4		204.9	
	Annual power generation (GWh/year)	7,988.3		571.46	
	Timely controllable installed capacity (%)	100		20	
	Reversible installed capacity (%)	34.85		0	
Affordability	Energy generation cost (c€/kWh)	0.65		0.75	
Efficiency	Demand covering capacity (%)	67.7		4.8	
Contributions to water security		**Total[1]**	**Relative[2]**	**Total[1]**	**Relative[2]**
Water access and supply	Water storage capacity (TU[1]: hm^3); (RU[2]: m^3/kWh)	6,821.5	0.85	555.8	0.97
	Water demand covering capacity (%)	176.2	----	20	----
Irrigation supply	Irrigation water provision (%)	43.5	----	24.3	----
	Water storage capacity of dams with energy-irrigation purposes (hm^3)	2,638	3.3 E-07	504	8.1 E-07
Environmental flows	Environmental flows (%)	34.8	----	27.14	----
Flood risk reduction	Flood risk regulation capacity (%)	34.8	----	5.07	----
Environmental impacts		**Total[1]**	**Relative[2]**	**Total[1]**	**Relative[2]**
Flow regime	Water withdrawal (TU[1]: hm^3) (RU[2]: m^3/kWh)	32,683	4.09	10,300	16.7
	Water consumption (TU[1]: hm^3) (RU[2]: m^3/kWh)	168.9	0.02	54.0	0.09
	Length of river with disturbed natural flows (TU[1]: m) (RU[2]: m/kWh)	752,279	9.41 E-05	345,230	5.52 E-04
Connectivity	Number of dams or obstacles	17	1.95 E-09	139	1.94 E-07
	% of scalable dams	0	---	51	----
Habitat loss	Reservoir surface area (TU[1]: ha) (RU[2]: ha/kWh)	28,476	3.56 E-06	10,980	1.78 E-05

[1]Total Units (TU): units for the absolute cumulative value, located in the **Total** columns.

[2]Relative Units (RU): units for the relative value, located in the **Relative** columns.

Table 5.2. Results for the hydropower indicators assessment

5.3.1. Contributions to energy security

Energy availability and efficiency

The number of plants is almost seven times higher for SHP than for LHP. Figure 5.3 also shows that SHP are more evenly distributed along the river, whereas LHP tend to concentrate in the downstream part of the basin. This suggests that SHP provides higher physical diversification of energy production, thus reducing the vulnerability to localized weather or human-related disasters such as regional droughts, floods, overflowing or breakage of dams because of the spatial decentralization of production.

LHP has larger installed capacity and energy generation capacity, which in both cases outweigh SHP by one order of magnitude, as shown in table 2. These results indicate that energy, LHP makes a considerably higher contribution to energy security than SHP.

As regards to security of supply impacts, LHP accounts for 100% timely controllable energy production and almost 35% of the installed capacity enabling energy storage through hydraulic pumping. Meanwhile, 20% of SHP installed capacity is timely controllable and it accounts for no hydraulic pumping and storage capacity. This illustrates the higher role played by LHP in ensuring grid stability and helping balance production peaks from other intermittent sources like e.g. renewable energy sources which are abundant in the Castilla Leon region (both solar and wind).

Affordability

In terms of affordability, both sources show similar production costs with an average 0.1 c€/kWh difference. However, these costs may vary for different projects.

Efficiency

When related to the regional demand, LHP production alone covers almost 70% of the regional energy demand, whereas SHP barely reaches 5%. This implies that in terms of efficiency of supply, LHP makes a considerably higher contribution to energy security than SHP.

5.3.2. Contributions to water security

Water access and supply

Total water storage capacity by LHP associated dams is 12 times higher than SHP dams. However, relative water storage per kWh of energy produced is slightly higher for SHP, with a difference of 0.1.

In terms of demand covering capacity, water stored by LHP dams can provide 120% coverage of regional water demands, whereas coverage by water stored in SHP only reaches 20% of regional demands. These results suggest that from a macro perspective LHP has a more important role and larger contributions to water supply in the basin than SHP. However, looking at the relative contributions, SHP provides higher water storage capacity per unit of energy produced.

Irrigation supply

The percentage of power plants associated to infrastructure also providing water for irrigation is almost double for LHP than for SHP. However, looking deeper into the numbers and the type of hydropower facilities that provide this service, it was observed that all the LHP were associated to a large multipurpose dam, which together summed a storage capacity of 2,638 hm^3, around 60% of total water storage capacity in the basin. Meanwhile, among the SHP providing irrigation services 32% were located in canals - either built mainly for irrigation purposes or for additional uses like urban water supply or recreation -, 14% were RHP with regulation capacity and 11% were RoR plants associated to small dams and ponds with irrigation canals derived. The cumulative storage capacity associated to SHP dams with irrigation purposes is 504 hm^3. In relative terms, SHP has a slightly higher water storage levels per kW generated than LHP. Although exact volumes of irrigation water supply associated with each type of hydropower development have not been estimated due to data availability constraints, the information above seems to support the initial result that LHP makes a higher contribution to water supply for food production than SHP.

Environmental flows

The results in table 2 show that the percentage of power plants identified as not complying with minimum environmental flow requirements during the 2015 water plan update revision was slightly higher for LHP, with 34% compared to 27%.

The authors considered interesting to also explore the composition of the group of SHP not meeting environmental flow requirements, in terms of type of technology applied (RHP or RoR). This is in order to check whether there was a predominance of RHP, which are mainly associated to big dams. It was observed that from those 27% that did not meet environmental flows, 27% were RHP plants whereas almost 68% were RoR. Thus RHP plants did not seem to have a dominant role in the non-compliance with environmental flows. Meanwhile, considering the overwhelming majority of RoR plants within the SHP development in the basin, with a share of 88% compared to 10% RHP – the remaining 2% corresponds to plants associated to a canal, as explained in section 2 -. The apparent preponderance of RoR plants within the SHP not meeting environmental flow requirements seems logical. However, further analysis with statistical tools would be advisable for higher accuracy and are recommended for further research as an important area of research for environmental flows.

Meanwhile, a particularly noticeable case of non-compliance with environmental flows was found in the Villarino plant associated to the Almendra dam (see Figures 5.3 and 5.4). Here the river Tormes, with an average inter-annual flow of 1200 Mm^3, is turned into a stream with a flow seldom exceeding 15 Mm^3.

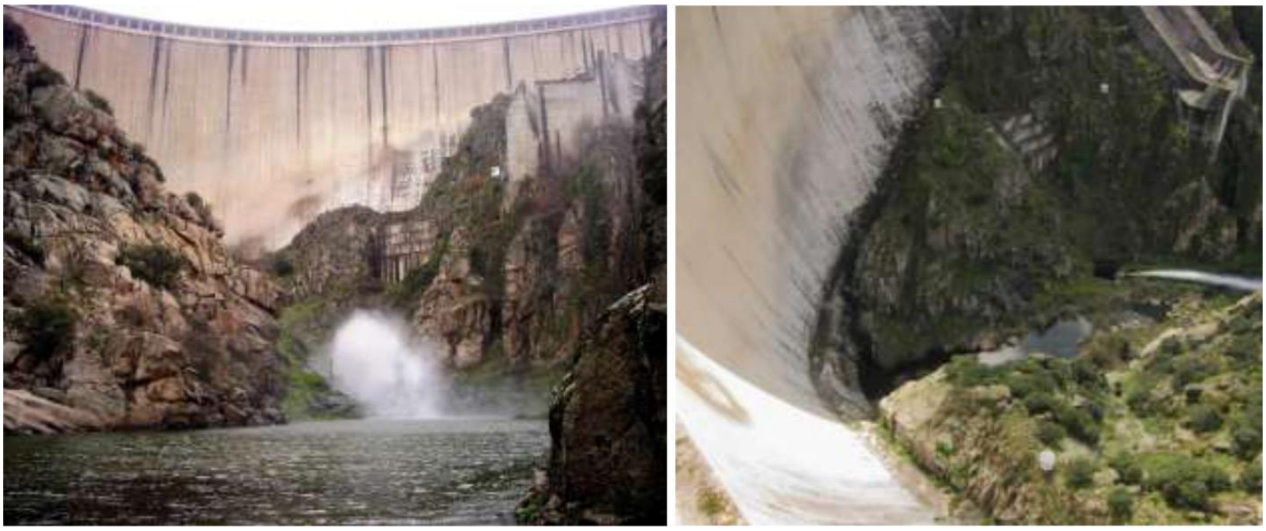

Fig. 5.4. Almendra dam shot from downstream (left) and upper view (right). The plume is the 'ecological flow' released through a Howell valve that never surpasses 500 liters per second. The water table in the forefront is contained in a little shock-absorber reservoir. Pictures taken by Ignacio Rodríguez.

Flood risk reduction

The percentage of power plants associated to a dam with a specific function and capacity for flood regulation is higher in the case of LHP, with 34% compared to a 5% for SHP. In the case of SHP, this characteristic is only present in RHP plants. However, in both cases the performance of a regulation capacity function is not inherent to the presence of a big regulation dam. It depends on whether it is operated to fulfil this function. This is an important finding since it demonstrates there is further room for management that can minimize impact on environmental flows. These results indicate that LHP has a higher contribution to water security in terms of flood regulation.

5.3.3. Environmental impacts

Flow regime

The results in table 2 show that the total amount of water withdrawn and turbined for energy production is four times higher for LHP than for SHP. Furthermore, in relative terms water withdrawals per kWh produced by SHP are three times higher, indicating lower water use efficiency of energy production.

In terms of water consumption, cumulative evaporation from dams associated to LHP exceeds that of dams associated to SHP by a threefold difference. It should be noted though that most of the evaporation from SHP comes from dams associated to RHP plants which have on average wider surfaces. In terms of relative consumption, SHP shows in turn higher water consumption per kWh produced, with a difference of 0.07 m^3/kWh. This difference is motivated by the presence of power plants with relatively low capacities associated to relatively big reservoirs.

The length of river affected is twice as large for LHP than for SHP. However, once more the relative impact per kWh is bigger for SHP.

Overall, the results indicate that the cumulative impacts on flow regime by LHP are considerably higher, whereas SHP has higher impacts per unit of output.

Connectivity

The number of dams or obstacles to river flow associated to each type of hydropower development is by far higher for SHP, which accounts for 139 dams compared to the 17 dams associated to LHP. In relative terms, SHP has also a larger number of dams per kWh produced, outnumbering LHP by two orders of magnitude.

In terms of scalability of obstacles, SHP accounts for 51% of partially scalable dams thanks to the installation of effective fish passes, whereas all the dams associated to LHP are completely unscalable. However, even though SHP dams account for a higher number of fish passes installed, due to the higher total number of SHPs, the number of unscalable obstacles is still four times higher for SHP than for LHP. Therefore, it can be concluded that SHP has considerably further impacts on river and ecosystems connectivity than LHP in the Duero Basin.

Habitat loss

The cumulative surface of land occupied by the reservoirs, thus causing a change of land use and habitat loss, is higher for LHP than for SHP, with almost a threefold difference. In turn, SHP shows higher relative impact, with a surface occupation per kWh outweighing that of LHP by an order of magnitude.

5.4. Discussion

The results of this study suggest that - in overall terms LHP - has higher contributions to energy and water security in the basin than SHP, with better performance in 10 of the 12 indicators assessed. As regards to the impacts, in absolute terms LHP generates higher cumulative impacts on flow regime and habitat loss, mainly driven by its greater magnitude, whereas SHP has higher cumulative impacts on river connectivity and ecosystems. Meanwhile, in relative terms SHP has higher impacts per unit of energy produced in all the impact categories, showing lower efficiency in terms of impact/energy performance ratio.

5.4.1. The potential role to increase energy security

Within the context of energy security, some aspects about the potential role of each type of energy development are worth highlighting.

First, the importance of diversification in the present context of climate change. The share and physical distribution of energy production is an increasingly relevant aspect considering the future predictions of climate change, which forecast average reductions in rainfall up to 5% in a scenario of 1°C temperature increase for the country, with river flow reductions between 5 and 14% and between 8 and 13% for the Duero basin (CEDEX, 2011). However, diversification should go hand in hand with minimization of impacts.

In the case of the Duero basin the concentration of LHP in the downstream part of the river poses high vulnerability to possible extreme events or localized attacks. SHP in turn is more widespread thus reducing the risks of a multiple collapse caused by a localized event. However, the amount of SHP power plants required to convey a comparable energy supply capacity is so big that even outnumbering LHP by seven to one they hardly manage to cover 5% of regional energy demand. Furthermore, they have considerable cumulative impacts on the river system. This aspect is also raised by Abbasi & Abbasi (2011), Bakken et al. (2012), Kibler & Tullos (2013) and Skinner & Haas (2014). In particular the extensive development of up to 22 cascading SHP plants as can be found in the Pisuerga tributary (see Figures 5.3 and 5.5) does not reduce risks from climate events. This is because they do not account for flood regulation capacity and the continuous slow-down of river flow velocity to the point of almost turning the lotic system into a lentic one in some of the stretches, which in turn, favours an increase of evaporation and can exacerbate the situation of water stress and water quality degradation in drought periods (Bond et al., 2008). Meanwhile, LHP at individual scale presents less vulnerability to rainfall variability due to the flexibility that the storage and regulation capacity and their potential function as a flood barrier endow them with (IEA, 2012; IDAE, 2011).

Second, in the aspect of security of supply the regulation capacity and especially the pumping and storage technologies offer a great potential to drive the Duero region and the whole of Spain towards a higher share of renewable and endogenous energy (IEA, 2012; IDAE, 2011). Hydropower plants with regulation capacity allow controlling the timing of energy production thus providing grid stability and offsetting the intermittent production of other renewables. Meanwhile, hydraulic pumping systems enable energy storage, avoiding the spill of surplus production from solar and wind peaks while providing a spillway for torrential flow during flood events. Despite only 3 of the 23 LHP plants having hydraulic pumping systems installed, there is the physical potential and the political intention to promote the necessary refurbishment to enhance these systems in all the Spanish basins, as reflected by the Spanish Renewable Energy Plan 2011-2020 (IDAE, 2011).

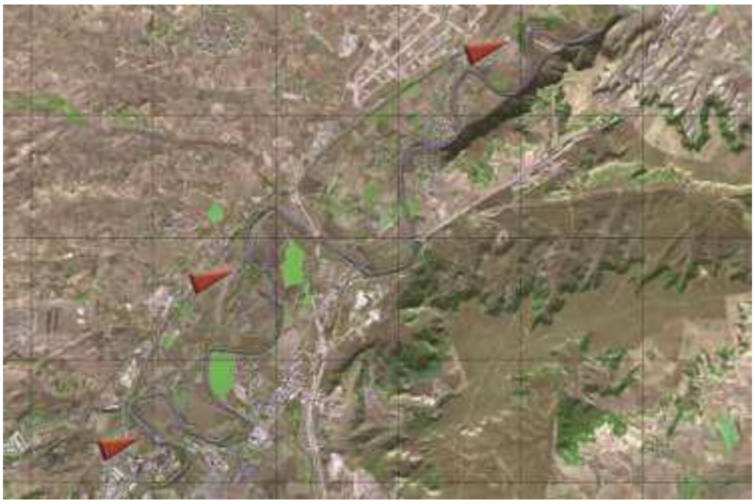

Fig. 5.5. Lower Pisuerga River, upstream Valladolid city. The arrows show the position of three weirs associated to three consecutive SHP. The length of affected stretch is 22.7 km and the medium slope is 0.03 %. The pool-riffle sequence has totally disappeared causing remarkable habitat loss and nutrient retention. As a result, the stretch becomes eutrophic in summer and the ecological regime has shifted from lotic to lentic (Ballarin & Rodriguez, 2013). Source: Iberpix. Instituto Geográfico Nacional, IGN. Grid scale: 2.5 X 2.5 Km.

In strategic terms, tapping the potential to couple low water footprint renewables to hydraulic pumping systems can allow for their expansion and competitiveness, while offsetting their production drawbacks, thus building a bridge towards higher endogenous, renewable and decarbonised energy supply (IEA, 2012) Furthermore, they could help reduce energy costs for i.e. irrigation by the provision of completely endogenous energy at a stable price, free of the risks of energy price volatility inherent to imported fossil fuels dependent energies like thermal power. Additionally, the promotion of hydraulic pumping coupled to low water footprint renewables could also contribute positively to water security by reducing the pressures on water resources from other local energy sources like thermal power and especially bioenergy (IRENA, 2015).

5.4.2. The potential for improvement on water security and environmental sustainability

In terms of water security, according to this study´s results LHP has a higher contribution to regional water security than SHP. However, it has been observed that the differential contributions do not depend upon the size or production capacity of the plants, but rather upon the type of plant – run-of-river plants or plants associated to reservoirs – and the additional functions of their associated infrastructure and management. For the case of water storage, for instance, a few low capacity SHP plants are located at the foot of big dams that provide considerable water supply. The irrigation water supply function is not performed by all large reservoirs, only by those with multiple purposes; whereas the canals and small dams that host some of the SHP are also used as diversion points for irrigation and even urban supply (i.e. Canal de Castilla). Meanwhile, the flood control function has to be balanced with the interests for hydropower production i.e. keeping the highest possible water level, which in the Duero basin is controlled by the ‘Commission on Dam WaterReleases’ with periodical release mandates adapted to the seasonal and river flow conditions.

When looking at the environmental performance, LHP shows larger cumulative impacts on flow regime and habitat loss due to the extensive occupation of space by the reservoirs and the subsequent loss of water through surface evaporation. This puts the myth that hydropower as a non-consumptive use of water into question. This could be true only in those cases where the hydropower project has been built in a previously existing dam, where the main water losses from the reservoir can be attributed to other priority users under Spanish law (urban supply, irrigation) and hydropower only makes profit from the water released. Although research on the exploration of methods to delimitate and assess the differential water footprint of each user in these cases is being conducted, there is not yet a fully agreed on validated method (Herath et al., 2011). In the remaining cases, this is when the hydropower project includes the creation of its own reservoir, when water is laterally diverted to be turbined downstream once the desired height difference is achieved, or when water is piped and transferred to another basin, there is a consumptive use with respect to the source water body.

In terms of river length, the extensive length occupation from the 17 biggest dams that feed LHP doubles the cumulative length disturbance by 140 SHP. A particularly extreme case is the stretch downstream of the Villarino power plant linked to the Almendra dam, where the river flow is reduced by 99% to the point of almost disappearing along a distance of over 17 kilometres. This adds up to the river length already disturbed by the reservoir. However, it should be noted that for these three metrics the impacts posed by RHP SHP plants are closer to the impacts of LHP than to those of RoR SHP plants, and highlight better the results of what could possibly be a more illustrative and worthwhile comparison: cumulative impacts from RHP vs RoR plants.

SHP in turn has larger impacts on river connectivity and further intrusion in natural protected areas due to the disproportionately larger number of plants. Even though none of the LHP have fish passes installed and SHP accounts for a 50% of plants with functional fish passes, the number of unscalable barriers to fish migration posed by SHP still exceeds LHP by four. Meanwhile, in terms of cumulative impact per unit of power produced, SHP has higher impacts for all the metrics analysed. Similar results were also obtained in other studies like Kibler & Tullos (2013), Zhao et al. (2012), Bakken et al. (2012).

In view of these results and considering two documented trends: the fact that most recent additions of hydropower capacity in Spain are not driving significant increases of hydropower production due to water resource limitations (Gómez, 2009); and the insignificant role played by the large number of SHP (especially those below 1 MW capacity) over the total hydropower production in the Duero basin (see Figure 5.6) indicates the need to undertake an optimization of the hydropower production scheme in the basin is recommended.

Big dams with high capacity hydropower plants associated are clearly playing a very important role for energy security in the Duero basin, and have the potential to provide very valuable services like water supply, extreme flood reduction and recreation. In fact, multipurpose dams are being increasingly claimed as an important element to move towards a green and sustainable economy (Berga, 2015; Branche, 2015).

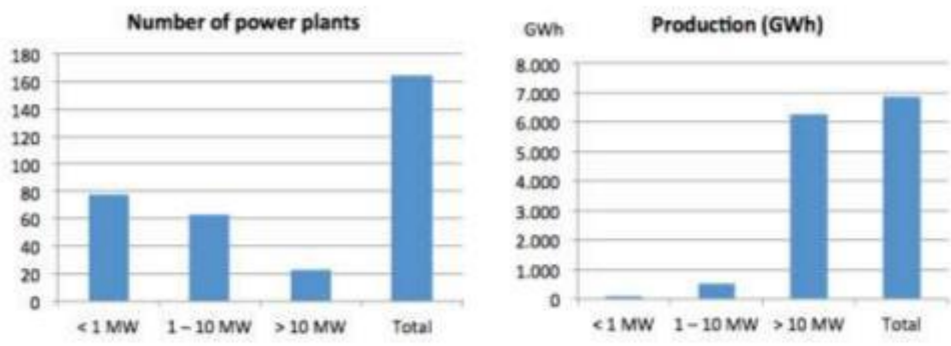

Fig. 5.6. Number of power plants and production by installed capacity range. Adapted from Polo, 2013.

However, these should be managed to get the maximum potential services while minimizing the infrastructure and impacts generated. Only a few of the big dams operating in the Duero basin are given a multipurpose use, while many of them are only used for hydropower production, irrigation or water supply. Reducing the number of small hydropower projects and concentrating energy production to better tap the potential created by already existing infrastructure could help reduce the cumulative impacts along the river, while maximizing the value-benefit/impact ratio of the projects.

Meanwhile, small capacity RoR projects could have a better application for decentralized production associated to irrigation canals or distribution pipe works, where energy production can be done using existing infrastructure without adding any additional disturbance to the river system (Ansar et al., 2014).

5.4.3. Reconsidering the definition of large and small hydropower

It has already been raised by several studies that the standard of installed capacity may not be the most appropriate for setting the difference between large and small scale hydropower, since it works as a poor indicator of biophysical impacts (Kibler & Tullos, 2013; Ziv et al., 2012; Gleick, 1992). It fails to differentiate two homogeneous categories of technological alternatives with significant differential and comparable characteristics in terms of environmental and sustainability performance, thus providing poor elements of judgement to inform decision making on future energy technology roadmaps. Other standards have been proposed as possible better division criteria, like the height of the head, the project design, the type of diversion device connected to or the type of turbine employed (Kibler & Tullos, 2013; Abbasi & Abbasi, 2011). The observations and particularities detected by the analysis in this study suggest that the type of plant - this is RHP or RoR - could work as a more functional and significant criteria, since it creates two categories conveying homogeneous technology designs that exert similar types of impacts and usually cover similar ranges of installed capacity and energy production.

Regarding the comparability of the effects of each type of hydropower development when the installed capacity is taken as the differential criteria, this study adds to other previously published work showing that a comparison of absolute impacts can provide a general picture of the global contributions and impacts at the basin scale. However, it also indicates caution in using it as the only basis to compare the extent of potential impact and environmental suitability (Kibler & Tullos, 2013; Bakken et al., 2012; Abbasi & Abbasi, 2011). An energy performance based comparison with a levelized assessment of cumulative impacts per unit of energy produced is required to attain consistent and scalable results. Furthermore, this study has not included macro socio-economic impacts, which are often determinant.

5.4.4. Study limitations

The study presents a series of limitations:

First, the availability of data has strongly influenced and limited the type of indicators and impact categories selected. Some important impact aspects like GHG gas emissions, impacts on water quality, solid sediment flows and a broader estimation of effects on aquatic biota could not be assessed due to lack of data and/or methodologies to evaluate their impact and should be included in future evaluations. Meanwhile, a more detailed analysis of the economic and social impacts related to the development of each type of hydropower scheme would be needed for a more complete and reliable evaluation of the performance in terms of energy security.

The indicators selected for the energy and water security assessments are aimed to provide a big picture of the differential contributions from each type of hydropower development, and some of them are expressed as relative values (%). For more accurate estimations a greater variety of indicators would be advisable and is proposed for further research studies.

The indicators selected for the *Connectivity* and *Disturbance of ecosystems* categories give a rather theoretical approach to potential impacts, based on the number of plants and devices installed. Due to time and resource limitations, no field work estimations could be performed. The authors recommend further research with more complex indicators and field work measurements to be carried out for a more accurate assessment on real impacts based on the collection of primary field data.

5.5. Conclusions

This case study has shown that the increasingly sound and apparent logic that small hydropower provides an alternative to tap the renewable hydropower potential with lower and more spatially dispersed impacts than large hydropower due to its smaller size and decentralized location is not as evident when it is massively deployed along a river system. In this case, the cumulative effects of a whole series of small plants cascading along thousands of kilometres, almost stopping the river flow and turning the lotic system into a lentic one, may reach or even outweigh the impacts of a few large scale projects.

In the case of the Duero basin, large hydropower has a critical role in ensuring regional water and energy security, and an inestimable potential to lead Spain towards a low carbon, low water footprint and less dependent energy system if the possibilities that enhanced hydraulic pumping systems coupled to intermittent renewables offer are envisioned and tapped. Currently, SHP generates higher cumulative impacts per unit of power generated in the basin for the three impact categories considered, mainly due to the massive number of existing plants. In absolute terms, LHP shows higher values for the impact indicators on *Disturbance of the river regime* and *Habitat loss*, whereas SHP shows higher impacts on *Connectivity*. Based on observations from the analysis, the authors consider that there might be great potential for optimization of the hydropower system by tapping all the possible services provided by existing reservoirs, some of which are single purpose, and concentrating hydropower production around existing infrastructure with potential for energy production (existing reservoirs or irrigation or distribution canals). This would enable reduced impacts compared to the current extended development of small individual projects that require their own diversion device.

Finally, an emerging lesson from the Duero and Spanish experience that could be scalable and transferable to water planning in other basins is the importance of prioritizing the premise of the maximum value with minimum intervention. Tapping and maintaining all the potential services provided by certain infrastructures like dams can prevent the need (and cost) of additional developments, thus reducing the cumulative impacts and maximizing the economic and sustainability value of the projects. Meanwhile, fair estimations of available resources and projections for their future evolution - and thus the real available potential for hydropower production or other services - should underpin any political decisions on infrastructure development to prevent falling in the misleading conception of 'the more quantity, the higher value and final output' instead of 'the more quality, the higher value and final variety of benefits'.

CHAPTER 6

THE WATER-HYDRAULIC FRACTURING NEXUS: COMPARING WATER AND REGULATORY CHALLENGES IN EUROPE (SPAIN) AND USA (TEXAS)

Chapter 6. The water-hydraulic fracturing nexus: comparing water and regulatory challenges in Europe (Spain) and USA (Texas)

6.1. Introduction

The development of shale oil and gas formations has been heralded as a game changer that has had - and will continue to have - repercussions for energy scenarios around the world. In the context of increased oil demand, changing oil prices, instability in key oil-producing regions, and the move away from nuclear energy, unconventional oil and gas are seen as transition fuels to a low-carbon future. This rosy future however has now come head to head with increasing concerns over water as a limiting factor.

This chapter summarizes the preliminary results of a study carried out along with Regina Buono and Elena López-Gunn that reviews and analyzes this recent energy revolution due to the growth of unconventional oil and gas reserves[13]. The objective of the study is to compare the relevant policies and regulatory frameworks around hydraulic fracturing in order to assess to what extent energy security has increased at the expense of water security. Particular emphasis is put on the water and energy nexus by examining two arid areas in the world where 'trading' water and energy securities could be particularly important: Texas and Spain. Each entity is a sovereign, self-governing, economic power existing within the context of a larger governmental or institutional structure (*i.e.* the United States and the European Union). This chapter analyses the regulatory frameworks for each, via a literature review, legal sources, and expert interviews, in order to evaluate the robustness of regulatory frameworks to prevent the reduction in water security as a consequence of the pursuit of energy security. The hydraulic fracturing industry in each case is at a different level of development, but these differences may be instructive. In particular, the experience of Texas, seen as the pioneer in the industry, may offer lessons for Spain as that country takes early steps into fracking exploration, albeit within a very different regulatory context.

6.2. Regulatory Framework: The United States and Texas

Water resources within the U.S. vary widely by region, as do the regulatory regimes governing water use, mineral extraction, and waste disposal, which are all generally governed by state law rather than federal law.[14] These differences make the states de facto laboratories with varying conditions from which other jurisdictions may draw lessons.

Water is scarce in Texas. The 2012 Texas State Water Plan reports a 2,700 Mm^3 gap between fresh water supply and demand in 2010, a number predicted to grow to 3,100 Mm^3 by 2060 if new sources of water

[13] A follow up of this work will be the production of a scientific publication presenting the final results in which the PhD candidate will be a co-author.

[14] The U.S. government does have the power to regulate how hydraulic fracturing operations are conducted on federal and Indian lands. In 2015, the Obama Administration issued a final rule intended to regulate hydraulic fracturing on these lands. The final rule includes new requirements for well-bores, imposes standards for interim storage of recovered waste fluids, requires notifications and waiting periods for parts of the fracturing process, and mandates disclosure of the chemicals used in the process via FracFocus (described in this article, below). A district judge in a case filed by the State of Wyoming, however, has stayed the rule, which was supposed to go into effect 90 days after issuance. Most federal lands are located in states other than Texas, so this article will not go into great detail about the regulation.

are not developed or substantial decreases in demand are not achieved (TWDB, 2012). The regulatory frameworks governing water and oil and gas in Texas are complicated. Oil and gas are regulated by the Railroad Commission of Texas (RRC). Jurisdiction over water is fragmented between multiple agencies. Surface water is largely handled by the Texas Commission on Environmental Quality (TCEQ), water planning and policy are the responsibility of the Texas Water Development Board (TWDB), and groundwater - to the extent it is restricted at all - is the provenance of local groundwater conservation districts.

This institutional context, in combination with on-going drought, has led to situations in which some Texans find themselves literally running out of water. The TCEQ maintains a list of public water systems that are limiting water use to avoid shortage (TCEQ, 2014). As of March 2014, ten systems were listed as at risk of running out of water within 45 days, and a further 19 were at risk of running out of water within 90 days (TCEQ, 2014). Fifty-two percent (52%) of Texas wells are located in regions of the state with high or extremely high water stress (Freyman, 2014). An investigation by the San Antonio Express-News found that water use in the Eagle Ford Shale far exceeded estimates of use put forth in a widely-cited study[15] by the University of Texas (Hiller, 2013). And there have been multiple reports of wells located near hydraulic fracturing operations running dry (Goldenberg, 2013, Houston Chronicle Editorial Board, 2013). These kinds of occurrences bode ill for the industry, in terms of its ability to sustain both operations and public support long term (discussed below).

Hydraulic fracturing not only requires considerable amounts of water for operations (between 2 and 6 million gallons or 6,000-10,000 cubic meters per well (NETL, 2014), but also generates vast amounts of wastewater in the form of flowback or produced water. Produced waters carry varying amounts of total dissolved solids (TDS), consisting of minerals and other substances dissolved from the formation or added by the operator. The TDS concentration may be five times as great as that of seawater (Gregory et al., 2011). There is not a consensus on the conceptualization of wastewater from the hydraulic fracturing activity. Some studies differentiate between ‘flowback’ water, referred to as the part of injected water that returns to the surface after a well is fractured (EPA, 2015a) and ‘produced or production’ water, regarded as the aqueous fluids that return to the surface after gas production begins (Brantley et al., 2014). However, industries do not make special distinctions between the types of water as far as management is concerned (Matthew & Mantell, 2011) and there is an increasing trend to consider produced water as all the water flowing out of the well after the fracturing process. This process may occur over a few days or a few weeks, depending on the geology and geomechanics of the formation (Gregory et al., 2011).

Despite having a pro-oil-and-gas mindset, arid Texas has experienced its share of public debate and controversy about the use of water resources for hydraulic fracturing operations. A study from the U.S. Environmental Protection Agency (EPA) showed that the main causes of aquifer contamination incidents in the U.S. were spills from surface pits and transportation of fluids, failures in well construction and water quantity constraints (Puls, 2012). It hence identified good performance in well construction as a critical aspect for the protection of water resources.

Relative to the needs of municipalities and agricultural interests in Texas, the amount of water required

[15] The study, funded by the energy industry, predicted that operations in the shale play would use a maximum of about 43 Mm^3 of water annually. However, in 2012, operators reported using approximately 54 Mm^3.

for fracturing operations is small, but the state has already determined that it does not have sufficient existing water supplies to meet the demand during drought (Texas Water Development Board, 2012), a condition from which the state has suffered for the last few years and that is likely to be common in the future. And, hydraulic fracturing operations are competing for water against powerful interests with long-entrenched water usage rights: irrigation for agriculture in Texas constitutes approximately 60% of the state's current water demand (Texas Water Development Board, 2012).

One of the most controversial questions surrounding fracturing concerns the possible contamination of aquifers and drinking water wells near operations (Osborn et al., 2011, Jackson et al., 2013, Vengosh et al., 2013). There is a lot of uncertainty surrounding the actual effects of hydraulic fracturing on nearby water wells. Findings by Jackson et al (2013), suggest that some homeowners living less than a kilometer from gas wells in the Marcellus Shale have drinking water contaminated with stray gases. An Associated Press review of complaints to regulatory agencies about well-water contamination in Pennsylvania, Ohio, West Virginia, and Texas found that pollution had been confirmed in a number of cases (Begos, 2014). But a study by Brantley et al (2014), also in the Marcellus Shale, was less conclusive. The authors found that, although evidence of contamination to surface and groundwater was rare, the analysis was impeded by lack of information (attributable to various causes but often perpetuated by liability or confidentiality agreements), pre-existing baseline water contamination, and rapid growth of the industry in the region. While significant water resource problems were uncommon, they were increasing through 2012 and the frequency of small incidents was high (Brantley et al., 2014, EPA, 2015b). In order to maintain or increase public acceptance of hydraulic fracturing, the authors called for more transparency surrounding the industry, including making data public and conducting additional investigations of environmental impacts.

Complaints and findings such as these underscore the importance of safe drilling practices and options for disposal of fracking wastewater that protect local water supplies. One option for managing wastewater is to inject it into an underground well. This option, however, depends on the availability of adequate disposal well capacity. Texas has thousands of wells for this purpose, whereas Pennsylvania—home to the Marcellus Shale and growing gas production—had only seven as of 2011 (Gregory et al., 2011). Anyone considering widespread fracking operations should evaluate the presence of these wells or the cost that would be required to build them, along with applicable laws—or lack thereof—governing their construction and maintenance.

But availability and expense are not the only issues that plague deep-injection wells. Some studies have shown that wastewater disposal via injection well poses some risk for induced seismicity, although reported events have been rare relative to the large number of disposal wells in operation (Committee on Induced Seismicity Potential in Energy Technologies, 2013).

Another option for managing wastewater is to treat the water, although this option may be constrained by regulation and expense or limited in effectiveness. Treatment works, particularly publically owned ones, may be restricted to accepting only limited amounts of various types of wastewater. For example, many treatment plants in Pennsylvania are prohibited by law from receiving volumes of oil and gas wastewater that exceed 1% of the average daily volume treated by the facility (Gregory et al., 2011). And, even if regulations do not limit the amount of waste that may be received by a treatment facility, the amount of flowback water produced, especially in a very active shale formation, may quickly exceed the ability of the facility to accept and treat the flows. Further, the effectiveness of treating hydraulic fracturing wastewater is uncertain: wastewater treatment is usually unsuccessful at removing salts and other dissolved solids in brines, and some rivers receiving Marcellus Shale brines have been shown to have high salinity levels (Soeder and Kappel, 2009).

Battles over legal authority and regulatory jurisdiction may also be costly impediments to investment in hydraulic fracturing. In the U.S., after state legislatures came out in support of fracking or failed to take a position against it, political subdivisions began enacting local regulations limiting or prohibiting the practice (Taylor, 2013). Many of these initiatives have been reversed under threat of lawsuit by the energy industry, struck down by the courts, or prohibited by state law (Karmasek, 2011, Hooper, 2013, Smith and Ferguson, 2013). In 2015, the Texas Legislature - in response to ordinances passed by the City of Denton and other Texas municipalities to prohibit hydraulic fracturing within city limits - passed a law granting the state exclusive jurisdiction over oil and gas operations, effectively prohibiting municipalities and other political subdivisions from banning hydraulic fracturing and limiting their ability to control where oil and gas wells can be drilled (H.B. 40, 84th Texas Leg., Reg. Session, 2015). Bans in other states, such as a zoning ordinance prohibiting fracking within the town of Dryden, New York, have been upheld by courts. In December 2014, the State of New York announced a ban on all gas development by hydraulic fracturing, citing a multi-year health study that showed the benefits of accessing natural gas resources did not outweigh the potential risk to public health (Wilson, 2014).

The U.S. legal system is unique in allowing landowners to also own mineral rights (Morse, 2014). This, along with robust capital markets to support exploration and experimentation and relatively less regulation, have created a situation that will be difficult for other countries to replicate (Hefner, 2014).

Operators in Texas are required to disclose via a website called FracFocus the chemical ingredients and water volumes used in the hydraulic fracturing of a well permitted after February 1, 2012 (16 Tex. Admin. Code § 3.29). FracFocus is a joint project of the Ground Water Protection Council (a national association of groundwater and injection control agencies) and the Interstate Oil and Gas Compact Commission (a national association of oil and gas regulatory agencies). Unless the information is protected as a trade secret under Texas law, any information disclosed is public information (16 Tex. Admin. Code § 3.29(2)(D)).

6.3. Regulatory Framework: The European Union and Spain

The European Parliament and the European Commission have chosen not to pass direct regulation on fracking at European level. In 2013, the Parliament voted to adopt an amendment to the Environmental Impact Assessment Directive (2014/52/EU), adding the exploration phase of non-conventional hydrocarbon projects using hydraulic fracturing techniques to the list of project types requiring assessment (Young et al., 2013). However, after deliberations and strong pressure by lobbyists, the amendment was reduced to a set of non-binding recommendations (European Commission, 2014), and a declaration of intent by the DG Environment to develop a series of 'robust and appropriate rules to accompany shale gas developments' (WWF, 2014). Thus member states were left with the responsibility to regulate the activity according to their national priorities, with the indirect support of other existing EU regulations. Applicable laws include the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Directive (2006/121/EC) for the use of chemicals; the Water Framework

(2000/60/EC), the Groundwater (2006/118/CE) and Drinking Water directives for the protection of water resources; the Habitats (92/43/EEC) and Wild Birds directives (2009/147/EC) for the protection of environment and ecosystems; the 20-20-20 Strategy and Air Directive (2001/81/CE) related to air emissions and climate change; and the Directive on Public Access to Environmental Information (2003/4/EC).

In Spain, the main regulatory competencies are owned by the central state, with some particular aspects in the hands of the autonomous regions. The central government has primary responsibility for the regulation of hydraulic fracturing. Despite the fact that, to date, no regulations have been passed specifically addressing hydraulic fracturing activity, the oil and gas sector, including conventional drilling activities, has traditionally been regulated centrally. Table 6.1 sets out Spanish laws that apply in whole or in part to hydraulic fracturing activity.

Name of Law	Law No.	Date Enacted or Last Amended	Competency
Hydrocarbons Law	34/1998	2007	Regulating royalties to the state, granting of permissions, operation requirements and reporting protocols.
Spanish Water Law	1/2001	2007	Regulating water aspects like priorities between uses, issuing of water concessions and discharge permits.
Groundwater Protection Law	1514/2009	2009	Regulating water aspects like priorities between uses, issuing of water concessions and discharge permits.
National Water Plan	10/2001	2005	Regulating water aspects like priorities between uses, issuing of water concessions and discharge permits.
Environmental Impact Assessment Law	21/2013	2013	Regulating the type of projects and activities that need Environmental Impact Authorization and the procedures to elaborate Environmental Impact Assessments.
Law on Natural Habitats and Wild Species	1421/2006	2006	Regulating the measures to protect biodiversity through conservation of natural habitats and wild species.
Law of Public Access to Environmental Information and public participation	27/2006	2006	Establishes the instrumental means to grant appropriate access for citizens to environmental information and allow public participation in environmental decisions.
Waste Law	10/1998	1998	Regulates on production, management and disposal of waste and promotion of reduction, recycling and valorisation.
Hazardous Waste Law	952/1997	1997	Regulates on the classification of hazardous wastes and the handling procedures.
Air Quality Law	34/2007	2007	Regulates on prevention, surveillance and reduction of atmospheric pollution.

Table 6.1. Summary of Spanish laws applicable to hydraulic fracturing

Regarding the Environmental Impact Assessment (EIA) legislation, in 2013 the Spanish government amended the EIA law to include specifically both the exploration and production phases of conventional and unconventional oil and gas projects using hydraulic fracturing techniques (BOE, 2013). In addition to the EIA, companies that seek a permit are required to provide a number of documents, including individual studies on seismicity, geology, geo mechanics, hydrogeology, water resources, archeology, biology, potential effects on the Nature 2000 Network, noise, and atmospheric emissions, as well as a waste management plan and an emergency plan (BNK Spain Director of Communications, pers. comm).

To date, most of the shale gas reserves have been identified in the Basque-Cantabric, Pirenaic, Ebro, Guadalquivir and Betic basins (CSCIM, 2013) and, as of 2014, around 70 investigation permits had been granted and another 60 applied for, as shown in Figure 6.1 (MINETUR, 2014).

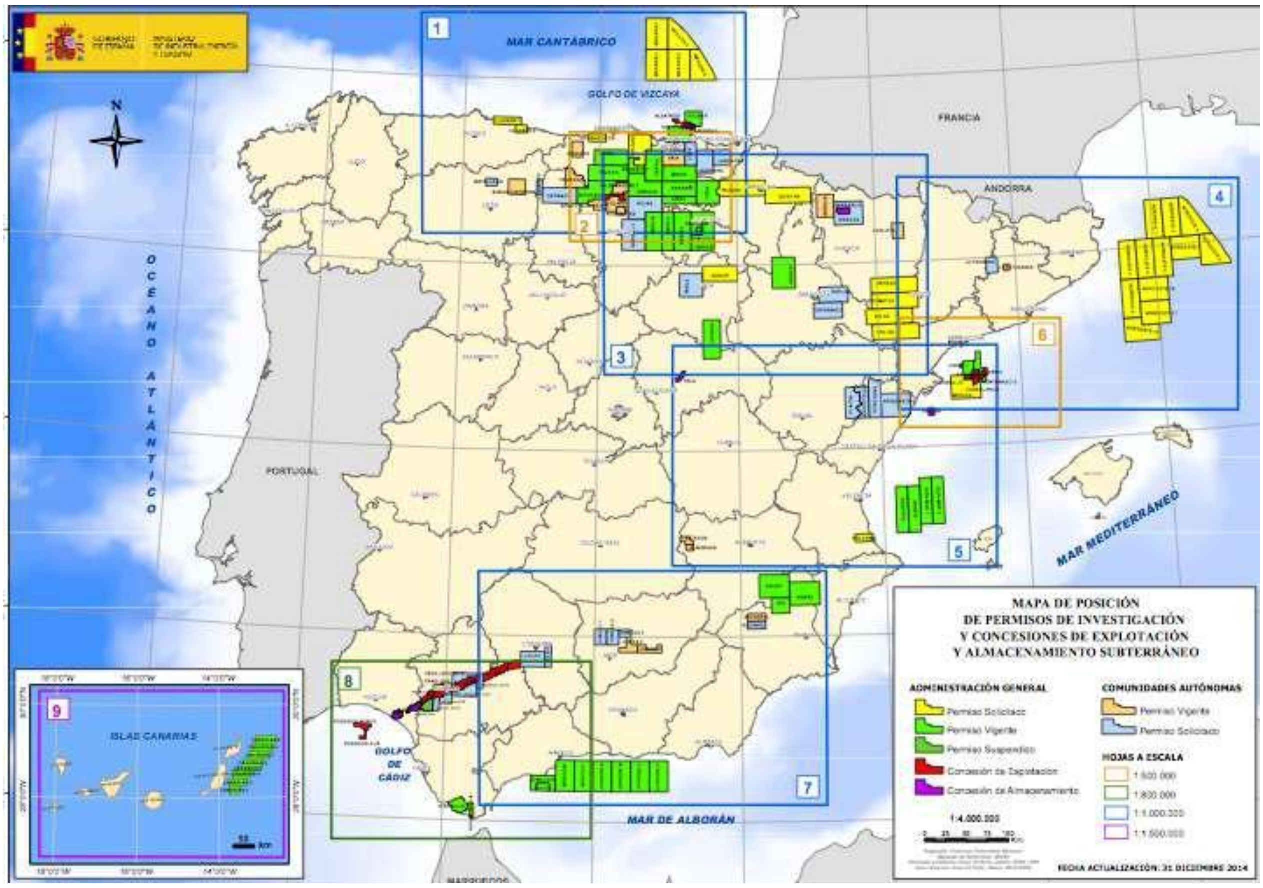

Fig. 6.1. Map of granted by the Spanish government as of 2013. Source: MINETUR, 2014

Spain's 17 autonomous regions are responsible for land-use planning and agriculture, and hold water competences for basins fully encompassed within the regional boundaries (non-transboundary basins). In view of the increasing number of hydraulic fracturing permit applications, the autonomous communities of Navarre, Cantabria and La Rioja in 2013 passed regional laws to ban fracking, but these were declared unconstitutional by the Constitutional Court in June 2014[16]. The regions are now taking steps to express the concerns of their citizens - expressed clearly in the 2015 regional and local elections - by other means. Examples include an initiative for an anti-fracking declaration signed by 102 mayors of regional municipalities in Cantabria; the collection of 30,000 signatures and marches against fracking in the Basque Country in July 2014; and the use by municipalities of land-use planning mechanisms (such as declaring lands susceptible to hydraulic fracturing to be protected areas) to stop the activity.

The implementation of water law and planning in Spain is done at the river basin scale. River basin authorities are responsible for the issuance and control of water permits for both surface and groundwater

[16] Cantabria: Law 1/2013, Abril 15th, suspended by the Constitutional Tribunal on February 11th, 2014, and invalidated by STC 106/2014, June, 24th; La Rioja: Law 7/2013, June 24th (BOLR del 24), , suspended by the Constitutional Tribunal on April 8th 2014, and invalidated by STC 134/2014, July 22nd; Navarre: Foral Law 30/2013, Octubre 15th y Agreement by the Junta de Cooperación Administración General del Estado-Comunidad Foral de Navarra in relation with that law, published in the Official State Gazette on January 27th 2014 (Sández-Arana, 2015).

withdrawals. All water resources in Spain are considered a public good (with some exceptions for groundwater) and regulated as such, and any withdrawal or use of water must be permitted and regulated by the relevant river basin authority. The basin authorities are also responsible for the elaboration of basin water plans and drought management plans, which set water use priorities based on the Water Law, National Water Plan directions, although these priorities can sometimes deviate in specific river basin plans. Water availability varies across regions, with higher mean rainfalls in the northern part of the country and lower rates with higher inter-annual and intra-annual variability and proneness to droughts in the center and the south. This variability, together with the seasonal rise in water demand resulting from the tourism industry and the irrigation season, makes the timing of water demands a very important issue in determining the margin of water availability for new uses like fracking.

Agriculture is the main water user in Spain, using 24,000 Mm^3 (65% of water withdrawals), followed by energy (8,250 Mm^3, 22%), urban uses (3,700 Mm^3, 10%), and industry (1,800 Mm^3, 5%) (Hardy and Garrido, 2010; Villarroya et al., 2014). The ranking of water use priorities varies slightly for different river basins, but usually sets urban water demand as the first priority, followed by energy or irrigation, depending on the basin, industry, recreation and urban irrigation. Environmental flows are a restriction on use rather than a specific demand, and are currently enshrined under the requirements of the EU Water Framework Directive which is supreme to Spanish law. In most basins, irrigation precedes energy in the list of priorities. These priorities differ greatly from the U.S., wherein the principle of 'first in time, first in use' generally prevails, giving priority to older water permits regardless of the type of use. Thus the feasibility in terms of water availability of a shale gas development in Spain will be highly dependent on the magnitude, location and timing of water requirements, and also on whether the location of the well occurs in so called closed basins or where there are legally overexploited aquifers.

Geographic and physical factors in Spain pose a very different scenario from that of Texas. In Spain, the extension, concentration, and high interconnectedness of the surface and groundwater network, which extends over 69% of the country's subsoil (DGA, 2006), makes it almost impossible to site hydraulic fracturing projects far away from drinking water sources. This, together with other spatial limiting factors such as the abrupt orography, relative concentration of human settlements, and relatively high amount of protected lands, leave a considerably limited range of potential locations for shale gas operations. The Spanish Hydrocarbons Law makes some specifications and requirements about the protection of wells, including the casing and cementing of those parts of the well transversing layers containing fresh water resources and hydrocarbons, though minimum distances to be exceeded below the end of such layers are not detailed. The law also requires the performance of pressure tests and the measurement and monitoring of all necessary variables and indicators in order to prevent damages or risks and allow for the characterization of the crossed formations. It includes a call stated in the law to take all necessary precautions in order to minimize the risks for human and environmental health and to commit to the best industrial practices.

Due to a lack of detailed and reliable information about the potential risks of hydraulic fracturing and the best operation practices, the Spanish government commissioned a study by the Spanish Geological Survey (IGME, in Spanish) to assess risks and best practices based on technical criteria and the knowledge reported from the U.S. This study was published in 2014 and gives technical guidance to operators and administrators, including water sampling and solely monitoring recommendations i.e. only recommendations on parameters to measure and suggestion of possible techniques (IGME, 2014).

Wastewater management is another critical issue and source of risk, and operators are required to provide a detailed management plan (Water Law 1/2001)). Unlike Texas and other U.S. states, where up to 95.2% of produced water was disposed through deep well injection in 2007 (Veil, 2009), this option will probably not be considered in Spain. Though in physical and technical terms there could be some feasible options (Ramos, pers. Comm.), the extreme social concern after the Valencia tremors (Reuters, 2013) and the increased seismicity episodes reported in Oklahoma and Texas (Darold et al., 2015; Hornbach et al., 2015) have prevented companies from considering the option (Former BNK Spain Director, pers. comm.; BNK Spain Director of Communications, pers. comm.). Nor would transportation and treatment of produced water in municipal wastewater treatment plants (WWTP) be an option, since these facilities usually lack the capacity or the appropriate technologies to treat high salinity. Moreover, many river basin authorities are still working to make water treatment reach all local communities, and the use of part of the public infrastructure to support hydraulic fracturing efforts would also be controversial (CHD, 2013b).

At this preliminary stage, wastewater management for exploration operations for which permits have already been granted will be done by hiring an external specialized waste management company to dispose of produced waters and other waste under the ‘hazardous waste’ status and regulation (BNK, pers. comm.). However, although this is an expensive procedure that can be feasible at small scale, it is too costly to be considered in later phases with a higher number of wells. At present, companies are proceeding cautiously in light of the uncertain regulatory and procedural contexts, since undertaking the first investigation drillings will be critical to obtain reliable information about the composition and volumes of produced water generated and make decisions on the best management options. These could include onsite treatment with mobile facilities, special WWTPs shared by various operators in cases of large development, and disposal to the sea after treatment for non-saline contaminants, among other options. Companies are turning their attention towards advances in the U.S. and in Australia, and starting conversations with the national water and wastewater technologies sector, which has a developed industry and extensive experience with desalination.

The management and disposal of wastewater, especially from industry, is strongly regulated and controlled by the River Basin Authorities through discharge permits and minimum wastewater quality standards. Nevertheless, the location of projects and delimitation of water sourcing and disposal points are important, since the limits between basins are sometimes close, and specific rules, procedures, protocols or even standards vary slightly between river basin water boards and plans. These differences can lead to legal turf wars or provide opportunities for companies to search for the less onerous regulatory regime. On the other hand, it also makes procedures for obtaining all the permits and documents cumbersome and time consuming for companies.

Regarding disclosure, there is no legal obligation for companies to make public disclosure of their activity in Spain, beyond the aspects reflected in the EIA report. The EIA process includes a public consultation step, in which the draft report is made available to the public, who can provide comments to be taken into account for the elaboration and approval of the final EIA report. However, no instructions are provided concerning what information related to fracking projects should be disclosed. A group of shale gas companies have launched an online information platform devoted to shale gas (Shale Gas Europe[17] and the national equivalent, Shale Gas España[18]), but these are still very basic and do not provide any sort of systematized open disclosure database such as the U.S. site, FracFocus. In Spain, an information platform intended to provide information about hydraulic fracturing to the public has been created by a local group in Burgos.[19] However, there is a clear positioning behind all these platforms, which is reflected in the content and messages. Thus, in Spain, there remains a dearth of objective and unbiased information and data.

From a social perspective, reluctance, distrust and extreme opposition—fostered by alarmist messages, the reputation of the oil and gas sector, and the fear of unknown changes—are gaining ground among the Spanish population. Hydraulic fracturing is said to be threatening water, and that is one of the most sensitive points for Spanish society. Water is strongly linked and embedded in Spanish culture as largely a semiarid country, with socially valued or important economic activities like agriculture or tourism dependent on water. There is a history of regional conflicts motivated by water, like the tensions between the communities of Castilla La Mancha and Murcia regarding the transfer of water from the Tagus River, and the perspective or remote possibility to have the water reserves polluted mobilizing people en masse (ECODES Director, pers. comm.). Meanwhile, economic incentives for nearby communities are not as strong as in the U.S. In Spain, a landowner has no rights over the natural resources lying beneath his property, and thus will receive no royalties from their exploitation. To try to compensate this fact and increase social incentives for the acceptance of the activity, the government has approved a tax to hydrocarbons production that will revert on the landowners and affected communities (Monforte, 2014). However, the economic viability of the tax for the case of Spanish projects is still not clear (El periódico de la Energía, 2014), and the social opposition remains strong since Spain has already experienced first-hand the risk of seismicity due to human activity (or that is perceived to be so by the public). In 2013, the Valencia region of Spain was shaken by a series of earthquakes - including a 4.2 magnitude quake - attributed to a gas storage project in a depleted oil reservoir under the Mediterranean Sea (Reuters, 2013; 'Spanish government blames offshore gas project for wave of earthquakes', 2013).

6.4. The whole picture: what are the key issues?

This section examines the similarities and differences that can be seen between the two jurisdictions under consideration and reflect upon what kinds of policy lessons may be drawn from comparing the different regulatory frameworks. It identifies a number of key issues, as shown in table 6.2. These are first the risk paradigms, the regulatory culture around risk management as well as public reaction; second, wether national authority is limited or plenary; third, which is the primary regulatory level in terms of scale; fourth, who benefits from royalties accrued (and thus the incentive system); and finally, and possibly the most interesting aspect from a comparative perspective, aspects related to disclosure and regulatory capacity.

[17] Shale Gas Europe: http://www.shalegas-europe.eu/
[18] Shale Gas España: http://www.shalegasespana.es/es/
19 Burgos Platform: http://fracturahidraulicaenburgosno.com/

	TEXAS	SPAIN
Regulatory cultures and public reaction	General acceptance/Risk assessment	Precautionary principle/ strong social opposition
Role of Central government	Limited	Plenary
Royalties	Landowner or leaseholder	State
Primary Regulation Level	State Law	Central Government
Disclosure/EIA	Disclosure required; trade secrets protected	EIA, but who regulates? Implementation capacity available?

Table 6.2. Key issues emerging from comparison of Texas and Spanish realities.

Regulatory cultures and public reaction

European policymakers who look to the U.S. boom as an example of the benefits of hydraulic fracturing would be wise to consider the vast differences in culture, including regulatory culture, between the U.S. and Europe in determining policy for hydraulic fracturing. Although the practice has encountered resistance among certain parts of the American public, this resistance has not had the effect of impeding development generally. Even prior to the commercial viability of the practice, U.S. law in all applicable areas at both the national and state level offered a welcoming environment for the development of the activity. In contrast, public resistance to hydraulic fracturing in Europe is widespread and has influenced policymaking and regulatory permitting decisions such that operations - including mere exploration activities - have been hindered (Heinz and Hiller, 2014). The most noticeable case is France, which has enacted a national law prohibiting hydraulic fracturing (Assemblée nationale et Sénat de la République Française, 2011). Public concern in Europe, in large part, centres on perceived risks for water resources, specifically regarding contamination or depletion (Heinz and Hiller, 2014). European law, more than U.S. law, tends to support the public's concern: EU law requires application of the precautionary principle (*Treaty on the Functioning of the European Union (Consolidated version)*, European Commission, 2000), to which the U.S. does not subscribe. The precautionary principle generally provides that, if it is suspected that an action or policy will cause harm to the public or environment, and scientific consensus to this effect is not present, the burden of proof of demonstrating the action is not harmful falls on he who would implement the action or policy.

Role of central government

Crucial to the proliferation of hydraulic fracturing (or any other practice or technology with potentially profound implications for the environment), is the ability, or inability, of central government to limit or incentivize the activity. In the case of Texas, this is limited since ultimately it is part of a full federal system (the U.S.) and thus there is an important presence of the EPA as national watchdog. Meanwhile in Spain the authority of the government is plenary, as a full sovereign state. The only restriction is the voluntary giving up of some sovereign powers to the European Union. However, since as we saw earlier the EU has opted not to directly regulate fracking, the full responsibility - apart from sectorial directives like those related to water or energy - rests with the Spanish government.

Royalties

Like all moments of technological change, one of the fundamental questions in hydraulic fracturing turns on who wins and who loses. Indeed, the rapid advancement of shale gas exploration in the U.S. has been attributed to a number of factors, such as the pre-existing oil exploration culture and the technological know-how, but one of the key factors has been the existence of individual property rights and the royalty payments they facilitate.

In the U.S., it is the landowner who largely benefits from the development of shale gas, either directly if he/she explores the well, or through royalties from granting an operator permission to explore and exploit any found mineral resources. Until recently this was not the case in Spain, or indeed in many European countries. Thus the trend in Europe, not just in Spain, intended to facilitate the development of hydraulic fracturing operations has been to revisit the issue of who benefits from shale exploitation. In the UK, for example, the royalties have been changed so that local municipalities also receive part of the benefits accrued from shale exploitation. Spain has followed a similar path, as discussed in Section 6.3. Primary opposition has been at the local level, where risks are perceived as highest. Indeed, in regions like Murcia the conflict has escalated between farmers and shale exploration companies due to competition for the same groundwater resources (and potential risk to shared aquifers). The case for regional government is more complex and in Spain a highly politicised game due to the electoral system.

Primary regulation level: regulatory oversight and capacity

As explained in section 6.2, in Spain the main competence for energy (and thus hydraulic fracturing) falls on the state level, the competences for water depend on the nature of the basin (whether transboundary or not) and for nature they clearly fall under the power of the regional governments. Thus the picture that emerges is complex, and makes for difficult oversight.

This aspect of regulatory capacity and oversight is actually a critical issue. At the moment in Spain the main regulations from the perspective of protecting water security are mediated on the one hand by the EIA and also by current water law. However, in relation to the EIA there is a potential conflict. The EIA falls under the responsibility of the regional governments, however, for the case of hydraulic fracturing the regional environmental departments have to vow to central government who has full competence over energy. Thus there is a potential conflict on two accounts: first, because those that ultimately have to decide on whether to grant the exploration permission are the same that those that have to invigilate whether environmental requirements are being fulfilled; and second, quite often the people at central government who take over the EIA duties are part of the Ministry of Industry, rather than the Minister of Environment and thus often lack the adequate in depth knowledge to regulate a complex issue. Indeed it boils down to a potential lack of regulatory independence and regulatory capacity.

An additional challenge in both Texas and Spain is the costs of data collection for a periodic monitoring of the activity. As mentioned before, i.e. the competent Spanish Administrations to undertake the inspections often lack the appropriate professionals to ensure their quality and reliability, and funds to hire external qualified professionals and equipments, namely in a scenario of high proliferation of hydraulic fracturing projects, may not always be available. This can pose an additional limitation to oversight. In this sense a great potential lies in organizing training programs to engage local people to participate in data collection, with a two-fold result: ensuring the required data collection at reduced costs while increasing a sense of ‘action being taken’ and personal implication to ensure the activity is being performed in a sustainable manner.

Disclosure

Disclosure and transparency are key issues to facilitate the government keeping track and control of the activity, as well as to reduce social reluctance and prejudice through reliable and accessible information.

As explained before, in Texas disclosure is done in a unified and standardized manner through a platform (FracFocus) created and managed in it greatest part by an impartial national institution aimed to safeguard the state of groundwater resource in the U.S. Such an initiative in Spain would endow an impartial and unbiased source of information for the government and the citizens that currently existing platforms do not provide. Meanwhile, a critical aspect is the involvement of technical and scientific institutions such as the Spanish Geological Survey (IGME) in the selection and definition of the types and formats of information to be disclosed, in order for it to be significant. However, ‘every law has its loophole’. Mechanisms to avoid full transparency like the ‘trade secrets’ in Texas are always found. However, a general trend towards increasing transparency and disclosure by companies in the U.S., even in those states where disclosure is not mandatory, points at a perceived win-win situation from all parties: companies gaining credibility, government gaining free and localized data sources and citizens having open – timeless[20] access to information on what is happening near their houses.

6.5. Conclusions

This study has analysed the entwined aspects of water security and energy security, particularly in the case of shale gas through hydraulic fracturing, and how trading to increase energy security entails several water and social implications, regardless of the political context. Some relevant and up-scalable messages can be drawn from the analysis. First, energy insecurity and the search for energy independence could potentially lead to water insecurity. Second, scale matters in water and energy security, since energy is usually regulated and managed at national level with global implications on trade and international markets, while water planning and management tends to be local or regional, and usually done at the basin scale, which seldom coincides with political boundaries. Third, risk reduction comes down to good regulation, but also to appropriate implementation and compliance monitoring, which are sometimes limited by existing capacities and resources. High levels of transparency and data availability can help reduce these limitations, and hence mechanisms and initiatives to promote them should be searched for by governing institutions.

Meanwhile, more specific lessons from the analysis on critical aspects to guarantee water security when opting for a non conventional natural gas path can be summarized in five critical points:

- *Baseline/monitoring:* The critical importance of performing baseline water quality assessments and periodic monitoring. This is essential to identify and track possible changes in water quality, as well as their origin, and apply the appropriate mitigation measures.
- *Application of best available practices and technologies:* companies should be required to demonstrate the application of best up to date knowledge and best practices, based on the most advanced technologies, in order minimize the risk of accidents or failures during the different project phases.

[20] As opposed to access limited to the one month period of ‘public consultations’ during the EIA elaboration procedure in Spain.

- *Participation:* Involving citizens, extension services, and/or country conservation agents in data collection and monitoring will be essential to increase credibility and the familiarity of people with the activity and ensure data availability. However, this will require providing the appropriate training to ensure data quality and comparability.

- *Regulatory Cost:* Development of inexpensive and easy-to-operate sensors operated by a mix of civil workers and volunteers to expand data collection. This will enable to balance and control the costs while creating employment.

- *Disclosure/EIA:* there is a need for better access to government and industry data. Besides the public information processes, a centralized database where available information from the government and industries are disclosed in a unified format would be advisable. The U.S. 'Frackfocus' platform can serve as an example, but other possible alternatives are also available.

CHAPTER 7

SYNTHESIS: CONCLUSIONS AND RECOMMENDATIONS

Chapter 7. Synthesis: Conclusions and Recommendations

The Water-Energy-Food Nexus approach has increasingly being recognised, framed and acknowledged as an important and necessary opportunity to address the upcoming water, energy and food security challenges. This thesis has provided an in-depth review of the origin and evolution of the WEF nexus concept; explored its main trends, challenges and uncertainties; as well as shown how - by applying a nexus approach for the identification of resource, policy and environmental trade-offs at the local scale - can help to understand better resource management conflicts and explore preventive and win-win mitigating measures.

Original and specific contributions to science and research on the nexus topic generated in this thesis include the following:

- An outlook of key nexus drivers, trends and challenges based on the expert knowledge from all over the world available in literature and gathered through methodologies like interviews and Delphi surveys.
- An outlook on the future evolution of key nexus variables based on the knowledge and intuition of a group of experts on the topic. The results complemented by qualitative explanations from the experts and compared to other scenarios and estimates in the literature provide useful triangulated results on trends and identification of points of dissent and potential factors that could influence the trendlines.
- A sequential and comprehensive methodology to perform WEF nexus analysis and diagnoses at different scales. The usefulness of this methodology is to help understand the WEF nexus implications for a basin, identify policy and management gaps and explore solutions through the application to the Duero river basin in Spain. This case also provides an accounting and characterization of nexus trade-offs in the region and provides recommendations on potential key planning issues for hydraulic fracturing development based on lessons learnt from the analysis of two case studies aspects to improve in order to avoid or minimise resource management conflicts.
- Evidence based knowledge on the potential contributions vs. impacts at a basin scale of an extended hydropower development through the assessment of the cumulative differential performance on water security, energy security and environmental impact indicators of the small scale and large scale hydropower schemes in the Duero basin.
- A set of critical aspects to be considered to minimize risks from hydraulic fracturing that cover very different contextual situations, geographical conditions, legal frameworks and hydraulic fracturing experience.

The following sections provide a summary of these contributions and the main conclusions attained in this thesis, and how knowledge generated could be upscaled to other regions. It also provides recommendations in two fields: first, future research in the nexus; and second recommendations for Spanish strategic water and energy decision making.

7.1. Contributions related to the WEF nexus framework definition, purpose and potential usefulness

The WEF Nexus approach provides a framework to promote a better understanding and consideration of water, energy and food interconnections, as well as informed and coordinated policy making, in order to achieve a sustainable and secure provision of water, energy and food resources. Chapter 2 of this thesis has presented a review and analysis of the different conceptual frameworks developed to date, with the following conclusions:

- First, WEF nexus frameworks usually consider the water-energy-food interconnections triangle as the core – in some cases a fourth axe is included i.e. land or fibre – surrounded by a sphere of other influencing drivers such as climate change, ecosystems, society and demography, policy and technology.
- Second, these frameworks are mostly aimed at three goals: 1. the understanding of trade-offs between these three elements; 2. the assessment of the consequences that internal and external changes can bring; and 3. policy responses that can positively address the possible implications for water, food and energy security. Some exceptions are targeted to a specific sector like energy utilities or the business sector.
- Third, although there is not unique and consensualised framework, all of them provide a similar structure tailored to the purposes and needs of the organization developing it.
- Fourth, these frameworks are usually accompanied by proposals for analysis/accounting methodologies and indicators, which allow the accomplishment of the goal underpinning their formulation. However, in some cases these can end up being conceptually complex, or too focused to the specific purpose being aimed for.

In this thesis the overall purpose of the WEF Nexus approach has been understood as providing a framework that aims and allows us to understand and quantify the complexity of the interconnections and flows between the three resources and sectors, in order to promote informed and coordinated policies.

Chapter 2 has also provided an analysis on the possible overlapping's or complementarities of this concept with other similar sectoral approaches aimed at integrated resource management, such as IWRM. The analysis led to the following conclusions:

- First, the peculiarity and main added value of the WEF nexus approach is that it is the first to mark itself out from a silos perspective and promote the consideration of multiple resources and coordination across sectors.
- Second, this approach provides an arena where the best know how of sectoral, integrative approaches, can be used to find synergies, opportunities and combined solutions that are implemented in coordination to encourage gains, while preventing conflicts derived from crossed efficiencies, conflicting policies or unintended consequences. From this standpoint, this thesis maintains that it can become a valuable frame for policy information, diagnosis and guidance when it includes i.e. a methodology that helps guide implementation in an ordered and comprehensive way.
- Third, this framework should not be limited to the political and institutional levels, since resource management is also relevant at business and household levels. It should be framed and applied in order to build resilience at all scales, covering as diverse actors and processes as an enterprise business model, an industrial production process, a small-holder farmer or a household manager.

In chapter 4, this thesis has based on a simple but comprehensive conceptualization of the WEF nexus approach to propose a **methodology for conducting WEF nexus assessments** consisting of three sequential analysis steps: first to analyse the nexus trade-offs, second to evaluate the level of policy integration and potential gaps, and third to identify related existing and potential conflicts and how these can be solved through synergistic solutions. This methodology can be used at any scale and provides a first picture for the overall situation. During the process, it also helps to identify connections to other drivers like climate change, societal aspects or ecosystems that can be later be further characterized through more specific assessments. This methodology has proved successful through its application to the Spanish Duero basin as a case study. The analysis provided a characterization and accounting of WEF flows that had never been done for the region before, which helped illustrate and understand the causes for certain existing conflicts, as well as identify policy coordination gaps and potential areas for improvement. The specific conclusions of this case study are further detailed in section 7.3.

A possible follow-up of this work could be the application of this methodology to other basins. It would allow to compare the extent to which failures/succeses in the consideration of water, food and energy policies drive similar conflicts/cooperation in different regions. An assessment of the variation in the range of intensity in these conflicts depending on regional characteristics (water availability, share of agriculture, agricultural income, etc.), the level of policy integration and the social contexts could help identify common and critical variables.

7.2. Conclusions and recommendations regarding key WEF interconnections, challenges and future research trends

The exercise of trends and uncertainties identification undertaken in chapters 2 and 3 of this thesis provides a complete view of the relevant and promising aspects with regards to facing present and future WEF challenges. This section will reflect on the most relevant conclusions and highlight key aspects where further research, efforts and considerations are needed.

A first aspect assessed through expert consultation was the perceptions on the different importance of the WEF nexus and its axes. The highest percentage of experts acknowledged that, to understand the complexity of the WEF nexus and address its multiple challenges, a holistic approach that looks at the whole system rather than at the different axes separately should be applied. However, it was also argued the water-food and water-energy axes have been given further research attention, possibly due to the consideration of water as the most critical element and an economic resource that cannot be substituted. The viewpoint maintained in this thesis is that **none of the axes should be underestimated, since certain trade-offs can acquire higher or lower importance depending on the regional context**. Important research efforts should be put on both a) understanding the whole system and its interconnections and b) exploring the different axes and their particular challenges, in order to further advance general nexus strategies and concrete solutions, to enhance the number of available alternatives and reduce the level of uncertainty. Based on this reflection, a general exercise to identify the most important challenges, uncertainty variables and trends for the nexus and the individual axes was conducted and presented in chapter 4. A summary of the results is provided in table 7.1.

AXIS	CHALLENGES	HIGH UNCERTAINTY VARIABLES	RESEARCH TRENDS
Common WEF	Data collection, processing and management	Unreliable and insufficient data	Data collection and management initiatives; qualitative tools; quantitative tools and models; risk assessment and multi-strategy planning; piloting and monitoring; spatial tools; TICs; auditing tools
	Groundwater overexploitation and depletion	*Rates of groundwater degradation*	Measuring and monitoring systems and sensors; groundwater replenishment and restoration; renewable energy for water pumping
	Increased resource demands and higher resource efficiency	*Evolution of water demands by sector*	Circular economy; water and energy metering; water productivity in agriculture; reduced food waste; water-energy conservation along the supply chain
	Increasing water availability constraints	*People affected by water stress; Alternative water resources in developed and developing countries*	Research on alternative water resources: desalination, water reuse and recycling; water as by product; rain water harvesting
	Sustainable Development Goals	*Access to water supply and sanitation*	Expansion and refurbishment of water and energy infrastructure
	Food waste	*Evolution of food waste rates*	Food waste reduction; resource efficiency along the supply chain; sustainable consumption
Water-energy	Energy thirst for water	*Impact of energy technologies on water quantity and quality*	Water accountings for energy; efficient cooling, water recycling and reuse practices; alternative injection fluids; low water footprint biofuels
	Water thirst for energy	*Evolution of energy requirements for urban water supply*	Energy accountings for the urban water cycle; low energy consumption devices; smart systems and technologies, energy production in WWTP; green infrastructure; coupled renewables-desalination; nanotechnologies
	Low carbon energies	*Impacts of shale gas on water resources Evolution of food prices*	Research on water trade-offs from hydraulic fracturing, first generation biofuels, CCS, hydropower
Water-food	Water pollution	*Wastewater treatmentin developing countries*	Water quality standards and monitoring; transparency platforms and disclosure; treatment of CECs; reduction of diffuse pollution
	Food thirst for water	*Evolution of global water markets*	Saline agriculture; resistant crops; efficient irrigation; water conservation; hydroponics and aquaponics; virtual water trade
	Higher living standards and changing diets	*Consumption patterns*	Awareness raising; eco-labelling; product certification
	Technological innovations	Potential effects of GMOs on human health	Biotechnology; genetic engineering; artificial foods; nanotechnologies; remote sensing; urban agriculture
Energy-food	Food thirst for energy	Regulations on energy self-generation	Smart tariffs; net metering; food preservation systems; energy self-generation
	Energy thirst for crops and food-biofuel competition	*Cultivated land surface*	Advance in second generation biofuels
	Alternative efficient solutions		Integrated food-energy systems; aeroponics; energy recovery from biogas and food/agro wastes; coupled renewables and energy self-production in agriculture; Decentralized onsite renewable energy systems in food supply chains

Table 7.1. Summary of Nexus challenges, variables of uncertainty and research trends identified. Variables in italics correspond to those selected for the Delphi exercise.

Projecting some of these variables into the future holds high levels of uncertainty, as shown by the wide range of scenarios and predictions that sometimes present very different or even contrary trends for the evolution of the same variable. The exercise performed in chapter 5 aimed to reduce this uncertainty by applying the Delphi methodology based on knowledge generation through promotion of virtual debate and consensus among experts. Expert's qualitative responses also provided additional information on factors that could drive a change on certain trendlines.

When combining the results from the Delphi study with the information gathered from elite and expert interviews (see chapter 1 on methodology), together with trends identified in literature, some issues of convergence and certain divergence were identified. Conclusions drawn from the final analysis on main nexus trends, as well as challenges and recommendations for future research are listed below.

- First, technological advances are very important to develop solutions for WEF nexus challenges. However, **non-technological aspects are highlighted as equally - or even more critical for an effective WEF sustainable management**. Some important challenges related to drivers on crosscutting issues may make the difference for these trends to become a reality. The identified drivers and related challenges with highest potential influence and impact on the nexus are shown in table 7.2.

INFLUENCE DRIVERS	KEY CHALLENGES
Climate change	Higher water scarcity, increased frequency of natural disasters, higher global temperatures, externalities from climate change mitigation policies.
Policy	WEF policy integration and coordination; water diplomacy and transboundary cooperation; implementation aspects and tools; collective and participative management; transparency, communication and capacity building; science-policy gap; foresight, adaptive and coherent planning; public-private cooperation; institutional reforms and cooperation; facilitating regulatory frameworks
Social	Access to information; social awareness; social acceptance of new technologies; valuation of indigenous knowledge; integration and empowerment of women and youth; collective thinking and community resource governance; social media for empowerment; unemployment, low salaries and social unrest; inequalities and migrations
Economic	Water, energy and food prices; financing challenges; cost of new technological developments; global markets; perverse subsidies and incentives

Table 7.2. Drivers and related challenges with highest influence on the WEF nexus.

Some aspects particularly highlighted by experts that this thesis would like to draw attention on are the following:

- The application of the Sustainable Development Goals and what has been called the 'Means of Implementation' - that is, the means and tools required for achieving the effective implementation of these goals. These will have a critical positive impact in solving WEF nexus challenges. This means of implementation include finance, technological, policy and governance, and capacity building aspects. For instance, there is confluence in the evidence that - in developing countries - the substantial investment needs for infrastructure enhancement and maintenance, together with the lack of solid institutions and political will, together pose the greatest challenge for the achievement of food, energy and water security.

- The creation of facilitating regulatory environments and the investment in capacity building and training programs are critical conditions to allow technological advances to enter the market, reach widespread application and optimal use, so they reach the target, purpose and level of results they are aimed to.
- Readjusting water prices to reflect the real value of the resource, as well as the cost of the service, will be essential for achieving responsible water use and make investments in water infrastructure economically sustainable.
- Avoiding perverse subsidies to promote certain energies or agricultural uses will also be critical to avoid energy-food competition and foster innovation and advances in the maturity, competitiveness and economic self-sufficiency of new or emerging technologies.
- Social awareness and information as the strongest drivers for change, and the prominent role played by social media for information diffusion.

➢ Second, a key emerging issue is the **possible negative implications from a shift towards a low carbon economy**, if water and food issues are not considered in energy-climate change mitigation planning. In particular, four technologies have been attributed with higher potential for risks and conflicts affecting water availability and integrity and/or food security: these are a) biofuels, b) hydraulic fracturing, c) carbon capture and storage (CCS) and d) hydropower when massively deployed. Delphi experts particularly highlighted two of them, biofuels and shale gas production through hydraulic fracturing techniques, as a key energy determinant for impacts on water resources. However, experts consider this expansion to be dependent upon the capacity and speed of technological innovation to reduce these impacts, as a condition not to be naturally phased out by the context.

- Biofuels. Future decisions and research on biofuels should focus on evaluating their sustainability from the standpoint of water and food trade-offs, along with impacts on soil nutrient cycling and land use, as opposed solely to benefits on GHG emission reductions.
- Non conventional gas. Several factors point at a fairly moderate mid-long term shale gas development scenario in Europe, which could be on the way towards extinction before it is even born in certain countries. These factors include a more precautionary legislative and political approach with pre-operation requirements (Spain, initially Poland); different geological, geophysical, spatial and demographic contexts; alternative energy strategic interests at country level (i.e. France and the nuclear industry); political concern and extreme social opposition (i.e. social movements in Spain); already emerging side impacts (i.e. Blackpool incident in United Kingdom) and uncertain economic viabilities partly due to the need to be exhaustively environmental protective. Overall, strong attention should be given to water availability, environmental protection and monitoring, coverage and implementation of regulations, application of best available techniques and technologies and social compensations when considering the viability of shale gas projects.
- Carbon Capture and Storage: CO_2 capture processes are conceived as a solution to reduce emission from thermal power processes, but all of them have a common point: an increase of up to 50% in water requirements per unit of energy produced compared to single thermal power plants. Delphi experts placed thermal power as the second energy with the highest impact on

water quantity and the third regarding impacts on water quality. Research is being conducted to overcome these limitations, by i.e. exploring partial capture to reduce negative effects on plant efficiency and treatment and re-use of wastewater to reduce water intensity, but regional water availability and variations should be critical aspects to be taken into account when deciding on plant locations.

- Hydropower: Delphi experts considered hydropower to have a great potential for expansion in emerging economies and rated them low in terms of water impacts compared to other technologies. However, they warned on the impacts for downstream users, ecological flows and water quality due to water retention and localized withdrawals. Chapter 5 of this thesis has showcased that, although at different magnitudes, both small and large scale hydropower projects have similar impacts; furthermore, when widely deployed along a river impacts from SHP can reach or even outweigh those of large scale projects with equivalent production capacity. Thus an argument, conclusion and recommendation resulting from this thesis is the need for careful pre-evaluation and strategic planning of potential hydropower developments at basin scale to avoid serious impacts on rivers and related ecosystems, while maximizing the potential benefits for energy and water security. This may be of great importance for regions like Africa, or regions currently implementing ambitious hydropower development programs, such as China or Latin America.

➢ Third, particularly **promising options are identified in the field of low water footprint renewable energies** (mainly solar and wind), either alone or coupled to other processes for centralized production (wind coupled to hydropower, for instance) or decentralized production (coupled to high energy consuming processes like desalination, groundwater pumping or water treatment and reuse). These options are identified in the literature and by experts as promising options to reduce the carbon footprint of energy while overcoming the water dependency problems. However, important research on reducing costs and how to solve the intermittency problem are required to make these energies competitive, and reach widespread adoption. Meanwhile, regulations that enable and facilitate decentralized self-generation and net metering from a legal and economic standpoint at both industry and user levels would also be critical to promote a transition towards renewable energy.

➢ Fourth, **renewables coupled to energy intensive processes such as desalination, water recycling or on-site treatment for oil and gas projects** can help to overcome the high energy cost limitations of technologies that would be key to reduce the pressures on water quantity and quality. Otherwise, Delphi experts envisioned a scenario where alternative water resources may only contribute to ease water stress in very specific areas and for certain uses. Water reuse and recycling are particularly seen in the literature and expert interviews as critical measures to reduce water withdrawals and enhance water use productivity. However, Delphi experts expressed concerns on the important barriers for widespread adoption, including the high treatment costs and social acceptance issues especially for certain uses (i.e. irrigation of crops that will later be eaten). This highlights **the importance on research efforts looking at the most suitable and economic treatments, optimal management of re-use streams and adjusting different qualities to the requirements of different uses**. In addition, the role of social awareness and education programs to reduce biases and promote acceptance.

In particular, renewable energies coupled to groundwater pumping, water withdrawal and conveyance, or decentralized energy generation can play a key role to reduce water and energy poverty around the world, especially in rural and remote areas. In the particular case of isolated communities, single small scale hydropower could provide a solution through the decentralized provision of energy and water, since the risk of accumulation from several nearby projects would be remote.

- Fifth, **approaches focused on closing the resource cycles and shifting towards a circular economy to decouple growth from natural resources demands** are highlighted by experts as an essential path to face future resource availability challenges. This includes not only water, energy and food but also strategic limited minerals (like phosphorus, lithium or certain rare materials), as well as the degradation and loss of biodiversity and ecosystems services (i.e. natural capital [21]). Related opportunities within the WEF nexus arena include energy and nutrient recovery in wastewater treatment plants, combined energy-water recovery systems in buildings and industries, recovery and valuation of wastes, among others. These initiatives are starting and should continue to be encouraged and promoted within the public and private spheres.

- Sixth, **efficiency and optimization are pillars that lie not only in technological advances but also in operation and behavioural practices**, and that can be promoted in all stages along the production, processing, distribution, consumption and disposal of water, energy and food resources. Efficiency involves minimization of inputs and losses, recycling of resources when possible, mechanisms to take advantage of possible surplus production, monitoring and reactive strategies to avoid rebound effects, as well as awareness raising on sustainable habits. Research on technological advances providing higher water and energy efficiencies (i.e. water efficient cooling systems, energy and water efficient irrigation systems) should be encouraged, but also accompanied with measures to control possible trade-offs and rebound effects on resource demand (i.e. lower water withdrawals but higher water consumption for cooling systems, or rebound effects causing overall increase of water or energy demands in irrigation).

Based on these conclusions, a series of recommendations towards the designing of future policy and research lines to address the WEF nexus are provided below:

- ✓ Thorough consideration of all nexus challenges, implications and policy needs in regional and national strategic policy making.
- ✓ Inclusion within the different international and regional research programs on research lines aimed at creating policy awareness and advancing tools and strategies to address these challenges.
- ✓ Creation of knowledge exchange platforms where successful experiences and achievements can be shared.
- ✓ Promotion and stimulation of research and deployment of renewable energies, particularly those with low water footprints, to increase competitiveness, reduce costs, and improve design and performance.

[21] Natural capital is defined by Robert Costanza (2008) as the stock of natural ecosystems that yields a flow of valuable ecosystem goods or services into the future.

- ✓ Research on market formulas and combined opportunities to facilitate and speed up widespread diffusion and adoption.

- ✓ Thorough consideration and evaluation of potential water and food trade-offs, including GHG reduction potential, when making decisions on energy technologies and future energy roadmaps at regional and national scales. Certain low carbon technologies can entail important water and food security externalities if trade-offs are not properly accounted for and managed. Climate change threats have set the reduction of carbon emissions as the main priority, but the additional consideration of other important environmental externalities is essential to design an energy mix that is sustainable in the mid to long term.

- ✓ Careful pre-evaluation and strategic planning for potential hydropower deployments at the basin scale to avoid serious damages to river and related ecosystems, while maximizing the potential benefits for energy and water security.

- ✓ Incentivize research on most suitable and economic treatments for re-use water, optimal management of re-use streams, adjusting different qualities to the requirements of different uses, as well as social awareness and education programs to promote social acceptance.

- ✓ Encourage research on coupled systems and synergistic solutions between existing technologies, with outstanding potential for renewable energies coupled to the urban water cycle.

- ✓ Encourage and facilitate decentralized energy production, consumption and net metering at the policy and regulatory levels. These elements can play a key role to reduce dependence on external energy; reduce energy poverty, especially in rural and isolated areas; increase energy security by promoting diversification; and build resilience against natural disasters and energy breakouts.

- ✓ Promote circular economy approaches both within the public and private sectors, as critical paths to decouple growth from natural resource use.

- ✓ Promote transparency within public and private institutions, with dialogues amongst stakeholders and the implication from civil society in WEF resource governance. These elements are key to build resource ownership and valuation, promote responsible management and use, create trust and cooperation between stakeholders and develop win-win strategies and solutions.

7.3. The case of Spain: conclusions and recommendations for strategic water and energy decision making

The three case studies developed in this thesis have addressed some of the most important challenges facing Spanish water, energy and food/agriculture policies, which are a direct consequence and reflection of the water-energy-food interrelations and interdependencies. These are the conflicts driven by the lack of a nexus approach and cross-policy integration, the debate on impacts and contributions from large and small scale hydropower deployment, and the concern over the potential risks for water security of a shale gas development in Spain.

In chapter 4, the Duero river basin has served as a pilot to identify and analyse conflicts driven by a poor understanding and consideration of WEF interconnections and a lack of coordination of WEF policies. The analyses performed through the application of the WEF nexus methodology proposed in this thesis led to the following conclusions:

- First, despite the existence of certain initiatives to account for energy and water trade-offs within water and energy planning respectively, remaining gaps are leading to important conflicts in the basin. The traditional lack of communication and cooperation between resource management authorities were found to lead to un-anticipated consequences and crossed water and energy efficiencies. Examples identified included rebound effects on water and energy demands by agriculture after an irrigation modernization process, lower aquifer levels driving more energy required for groundwater pumping, impacts on river regimes and fish biota caused by hydropower and social unrest in view of the potential deployment of hydraulic fracturing projects.

- Second, increasing energy prices were identified as a driver for several conflicts in the region. Examples included unaffordable wastewater treatment in rural communities or increasing energy bills constraining the economic viability of irrigated agriculture.

- Third, despite some initiatives have already been started by the River Basin Authority to deal with these problems, further dialogues and cooperation between the water and energy institutions and stakeholders would facilitate achieving synergistic win-win solutions to problems that cannot and should not be tackled from a silo perspective by one of the parts in isolation.

Based on the results of the analysis, specific suggestions are provided that can be also applicable to the national level and other Spanish basins.

- ✓ Elaboration of pre and ex-post analysis of water, energy and food/agricultural projects exploring possible trade-offs and evaluating performance.

- ✓ Evaluation of the energy footprint of irrigation modernization and the consideration of this assessment parameter within the next stages of water planning (2015-2021).

- ✓ Inclusion of a public participation stage within the energy planning process, like in the case of water planning, where civil society can express their opinions and concerns on energy policy decisions through a more participative management and planning.

In chapter 5, the Duero basin mirrors the impacts and contributions for water and energy security brought about by the vast hydropower deployment undertaken in Spain during the 20th century, while revealing a great potential for improvement opportunities. The comparative analysis of the contributions of large (LHP) and small (SHP) scale hydropower schemes led to the following conclusions:

- LHP has a critical role in ensuring regional water and energy security and a large potential to lead Spain towards a low carbon, low water footprint and less dependent energy system if the possibilities that enhanced hydraulic pumping systems coupled to intermittent renewables offer are tapped.

- Currently, SHP generates higher cumulative impacts per unit of power generated in the basin for the three impact categories considered (*Flow regime*, *Connectivity and Habitat loss*), mainly due to the massive number of existing plants. In absolute terms, LHP shows higher values for the impact indicators on *Flow regime* and *Habitat loss*, whereas SHP shows higher impacts on *Connectivity*.

- There might be great potential for optimization of the hydropower system by tapping all the possible services provided by existing reservoirs, some of which are single purpose, and concentrating hydropower production around existing infrastructure with potential for energy production (existing reservoirs or irrigation and distribution canals). This would enable reduced impacts, compared to the current extended development of small individual projects that require their own diversion device.

- In reference to the debate on the appropriateness of taking the installed capacity as the standard to set the difference between large and small scale hydropower, this thesis argues that it fails to set two homogeneous categories for technological alternatives that enclose significant different comparable characteristics in terms of environmental and sustainability performance. Thus this provides poor elements of judgment to inform decision making on future energy technology roadmaps. Observations from this analysis suggest that the type of plant - this is Reservoir Hydropower (RHP) plants or Run of River (RoR) plants - could work as a more functional and significant criteria, since it creates two categories conveying homogeneous technology designs that exert similar types of impacts and usually cover similar ranges of installed capacity and energy production.

Based on the Duero and Spanish experience, two main recommendations can be drawn for regions currently planning for high hydropower developments, like in the case of China, Africa and Latin America.

- ✓ The importance of prioritizing the premise of the maximum value with minimum intervention. Tapping and maintaining all the potential services provided by dams can prevent the need (and cost) of additional developments, thus reducing the cumulative impacts and maximizing the economic and sustainability value of the projects.
- ✓ The critical importance to make fair estimations of present and future availability of water resources before planning on the number and location of projects to be developed. This should prevent exceeding the point when additional installed capacity does not translate into additional energy production, but it does entail additional impacts on the river system.

Chapter 6 provided an overview of the main water security challenges posed by the deployment and expansion of hydraulic fracturing projects, by comparing the incipient situation of Spain with a case of advanced deployment stage in the U.S.: the state of Texas. The study showed important contextual differences in aspects related to the regulatory cultures and public reaction, role of central government, regulation capacity and oversight, royalties and disclosure. Conclusions on relevant aspects for water and energy security emerging from the hydraulic fracturing-water case included the following points.

- First, energy insecurity and the search for energy independence are increasingly leading to water insecurity.
- Second, scale matters in water and energy security, since energy is usually regulated and managed at national level with global implications on trade and international markets, whereas water planning and management tends to be local or regional, and usually done at the basin scale, which seldom coincides with political boundaries.
- Third, risk reduction comes down to good regulation, but also to appropriate implementation and compliance monitoring, which are sometimes limited by existing capacities and resources. High levels of transparency and data availability can help reduce these limitations, and hence mechanisms and initiatives to promote it should be searched for by governing institutions.

Meanwhile, more specific lessons from the analysis on critical aspects to guarantee water security when opting for a non conventional natural gas path can be summarized in five critical points:

- **Baseline/monitoring:** The critical importance of performing baseline water quality assessments and periodic monitoring. This is essential to identify and track possible changes in water quality, as well as their origin, and apply the appropriate mitigation measures.

- **Application of best available practices and technologies:** companies should be required to demonstrate the application of best up to date knowledge on best practices and the most advanced technologies, in order minimize the risk of accidents or failures during the different project phases.

- **Participation:** Involving citizens, extension services, and/or country conservation agents in data collection and monitoring will be essential to increase credibility and familiarity of people with the activity and ensure data availability. However, this will require providing the appropriate training to ensure data quality and comparability.

- **Regulatory Cost:** Development of inexpensive and easy-to-operate sensors operated by a mix of civil workers and volunteers to expand data collection. This will enable to balance and control the costs while creating employment.

- **Disclosure/EIA:** there is a need for better access to government and industry data. Besides the public information processes, a centralized database where available information from the government and industries is disclosed in a unified format would be advisable. The U.S.

  'Frackfocus' platform can serve as an example, but other possible alternatives are also available (i.e. frackprint).

As a final contribution, based on the three case studies this thesis proposes a series of highlights and recommendations for present and future Spanish water and energy planning.

Regarding the planning and implementation process:

- ✓ The importance of performing ex-ante and ex-post analysis for water, energy and food/agricultural projects exploring possible interconnected effects, designing preventing and compensating measures, and undertaking monitoring and evaluation activities during and after the project.

- ✓ The evaluation of the energy footprint of irrigation modernization and the consideration of this assessment parameter within the next stages of water planning (2015-2021, 2021-2027).

- ✓ The inclusion of a public participation stage within the energy planning process, as in the case of water planning, where civil society can express their opinions and concerns on energy policy decisions through a more participative process.

- ✓ The importance of prioritizing the premise of the maximum value with minimum intervention. Tapping and maintaining all the potential services provided by certain infrastructures like dams can prevent the need (and cost) of additional developments, thus reducing the cumulative impacts and maximizing the economic and sustainability value of the projects. Meanwhile, fair estimations of available resources and projections for their future evolution - and thus the real available potential for hydropower production or other services - should underpin any political decisions on infrastructure development to prevent falling in the misleading conception of 'the more quantity, the higher value and final output' instead of 'the more quality, the higher value and final variety of benefits'.

- ✓ Related to the previous one, the importance of scaling up when making decisions on water and energy technologies and infrastructures. Potential impacts should not only be evaluated on the basis of a single project. Considering the accumulation factor and performing ‘bird’s eye view’ studies of the macro effects at the basin or regional scale is essential to make planning that not only accounts for present sustainability and security challenges, but also prevents future challenges and promotes resilience in the long term.

Regarding technological decision and surrounding regulatory environment:

- ✓ The support and expansion of renewables is key to advance towards energy sustainability. Different opportunities lie in the implementation of hydraulic pumping and storage systems, coupled wind-hydropower given the large existing potential, small hydropower as solutions for decentralized production in certain rural areas, expansion of the solar power capacity, among others.

- ✓ Reconsidering some aspects of Spanish energy legislation would be required. A regulatory framework and incentive scheme that promotes renewable energies in line with the European goals are essential to ensure the advancement of Spain towards a decarbonized, sustainable and independent energy system. Meanwhile, energy self-consumption should be regulated to facilitate decentralized solutions that reduce environmental impacts and have higher economic benefits for farmers, in spite of going against the interests of the strong electricity companies´ lobby.

- ✓ A careful assessment of the feasibility of hydraulic fracturing projects in terms of water resources availability and security should be made, if the activity is to be deployed. Aspects to which the government should play critical attention are performance of baseline assessments and periodic monitoring, application of best available practices and technologies, creation of participative systems for data collection and monitoring, study of cost effective formulas to ensure appropriate monitoring and follow up of the activity, and public and private disclosure and transparency through centralized and unified databases or information platforms.

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Annex 1. List of publications, presentations and conferences

Published articles

Mayor, B., López-Gunn, E., Villarroya, F. & Montero, E. (2015) Application of a water-energy-food nexus framework for the Duero river basin in Spain. *Water International, DOI:10.1080/02508060.2015.1071512*

Accepted articles

Mayor, B., Rodríguez-Casado, R., Landeta, J., López-Gunn, E. & Villarroya, F. (2015) An expert outlook on water security and water for energy trends to 2030-2050. *Water Policy*, In Press.

Mayor, B., Rodríguez, I. & López-Gunn, E. (2015) Water and Energy Nexus: Bringing Perspective Over the Role of Large and Small Scale Hydropower in the Duero Basin (Spain). In: *Hydro 2015 Conference Proceedings, October 24-26th, Burdeaux, France.*

Other publications with the UCM and Water Observatory

Dumont, A., Mayor, B. & López-Gunn, E. (2013) Is the Rebound Effect or Jevons Paradox a Useful Concept for better Management of Water Resources? Insights from the Irrigation Modernisation Process in Spain. *Aquatic Procedia, Vol. 1, pp. 64–76*

López Gunn, E. et al. (2013) Rethinking Integrated Water Resources Management: Towards Water and Food Security through Adaptive Management. Chapter in: Willaarts, B., Garrido, A. & Llamas, R.M. (Eds) (In press) *Water and Food Security in Latin America. Social, Economic and Environmental Implications for a Fast-growing Region*. United Kindom, 230 pp.

Presentations

Co-author in the presentation: Lopez Gunn, E., Buono, R.M. & Mayor, B. (2014) Trading Securities? A Comparative Study On Regulating Fracking In Europe (Spain) And Usa (Texas). In: 2014 World Water Week, 31/08 – 05/09/2014, Stockholm, Sweden.

Presentation of the ‘Delphi Study on trends in the interrelations between legislation, water and energy to 2050’ by Beatriz Mayor representing the UCM-Repsol team within the ‘Informal Side Breakfast Meeting: Legal and tenure aspects on water and energy’ session at ‘2014 UN-Water Annual International Zaragoza Conference. Preparing for World Water Day 2014: Partnerships for improving water and energy access, efficiency and sustainability’. 13th-16th January 2014.

Presentation of Phd objectives at the ‘2013 Europaeum Graduate Workshop on Climate Change, Water and Cities: what future for Europe?’ hosted by the Amsterdam International Water Week forum and Leiden University, 5th – 7th November 2013.

Main attended conferences:

MASE Workshop entitled 'La explotación intensiva de acuíferos en España: retos y soluciones tecnológicas para su gestión eficiente' celebrated at the Spanish Engineering School, Madrid, 14th April 2015.

Diverse water footprint seminars and session celebrated by the Water Observatory in the Botin Foundation Headquarters in C/ Castelló 18, Madrid.

Support in the preparation and conduction of the *'2015 UN-Water Annual International Zaragoza Conference. Water and Sustainable Development. From Vision to Action'*. Zaragoza, 14-17th January 2015.

'Oklahoma Governors Water Conference' organized by the Oklahoma Water Resources Board. 22-23rd October 2014.

'Ground Water Protection Council Annual Forum' on hydraulic fracturing and groundwater protection, and the *'National Rural Water Association WaterPro Conference'* events, Seattle, Washington, 5-8th October 2014.

2014 XI Annual Workshop: *'Cátedra Rafael Mariño de Nuevas Tecnologías Energéticas: Usos del Agua en las Nuevas Tecnologías Energéticas: Hidrocarburos No Convencionales y Geotermia'*. Universidad Pontificia de Comillas, Madrid, 28th May 2014.

'*Jornada Sobre Hidrocarburos No Convencionales'*. Universidad de Burgos. Burgos, 24th April 2014.

'2014 UN-Water Annual International Zaragoza Conference. Preparing for World Water Day 2014: Partnerships for improving water and energy access, efficiency and sustainability'. 13th-16th January 2014.

Annex 2. List of experts participating in the Delphi study and Interviews, expertise and institutional profile

NAME	TYPE OF INSTITUTION	EXPERTISE	Participation
Adriano García-Loygorri	Ministry of environment	Advisor to the Water Director, and main ministry representative in water-energy related events. Former chief of the Cooperation Fund for Water and Sanitation Department at the Spanish International Cooperation Agency (AECID).	Delphi questionnaire
Alberto Garrido	University/Research Institute	Professor of Agricultural and Natural Resource Economics, Dep. Director of the CEIGRAM and Dep. Director of the Water Observatory-Botin Foundation. Sound research experience and relevant publications on water, energy and agricultural issues like water accountings, water-energy nexus and the links with irrigation.	Delphi questionnaire
Carlos Benítez	Private company	Agricultural engineer with experience in water planning and management, water scarcity and drought management and environmental flows.	Delphi questionnaire
Carolina Rodríguez	Research Institute	Spanish Delegate in Climate Action, Environment, Resource Efficiency and Raw Materials - Horizon 2020. Expert in resource efficiency, environmental technologies and innovation projects.	Delphi questionnaire
Darío Salinas	Institute of Geopolitics	Expert at the French Institute of Geopolitics (University of Paris VIII) in water policy and geopolitics, with specialization in European Union and the Mediterranean region.	Delphi questionnaire
David Sauri	University	Expert in natural risks, water and land management and global changes.	Delphi questionnaire
Eloy García	Research Institute	Director of the IMDEA water institute. Expert in environmental technologies, applied urban water management and technology transfer.	Delphi questionnaire
Emilio Custodio	University-Research Institute	Emeritus Professor. Expert in groundwater hydrology, hydrochemistry, environmental isotope techniques, aquifer recharge and water resources.	Delphi questionnaire + elite interview
Enrique Cabrera	University	Professor of Fluid Mechanics. Expert in the water-energy nexus in urban infrastructures, services, planning and policies.	Delphi questionnaire
Javier Uche	Research Institute	Director of the Natural Resources Area at CIRCE. Expert in thermoeconomy, desalination, life cycle analysis (LCA), water and energy integration (polygeneration), exergy analysis of natural resources	Delphi questionnaire
Joan Corominas	Public Water Management Institution	Agricultural engineer and expert in hydrology, irrigation and water planning. Responsible for the Irrigation Modernization Plan in Andalucia (Southern Spain)	Delphi questionnaire + elite interview
		Research fellow at CITA (Government of Aragon).	

José Albiac	University	Expert in natural resource and environmental economics, working in hydro-economic modelling, nonpoint pollution and climate change.	Delphi questionnair e

NAME	TYPE OF INSTITUTION	EXPERTISE	Participation
José Luis González Vallvé	Private Association – University	Director of the Spanish Water Utilities Association. Expert in water supply infrastructures and technologies; Deputy chief of the Spanish Division at the European Commission, coordinating investments related to the European Cohesion and Structural Funds for water and energy infrastructure and planning, among others.	Delphi questionnaire
Josefina Maestu	International Organization	Director of the UN-Water Decade Programme on Advocacy and Communication (UNW-DPAC), specialized in water economics and organizer of the 2014 UN-Water Annual International Zaragoza Conference. Preparing for World Water Day 2014: Partnerships for improving water and energy access, efficiency and sustainability.	Elite interview
Maite Aldaya	International Organization	Consultant at UNEP and the UNW-DPAC and former member of the Water Footprint Network. Specialized in water accountings, water footprint and water use efficiency.	Delphi questionnaire + elite interview
Manuel Pulido-Velázquez	Research Institute – University	Expert in water economy and management models, and water policies. Participation in the AQUATOOL model.	Delphi questionnaire
Mariano Cabellos Velasco	Non Governmental Organization	President of Energy without Frontiers. He has developed projects of access to energy and water in developing countries. Member of the Spanish Energy Club.	Delphi questionnaire
Ramón Llamas	Research Institute	Director of the Water Observatory, Botin Foundation. Internationally recognized expert in water footprint, groundwater, silent revolution of water and water governance.	Elite interview
Tony Allen	University	Emeritus professor at King’s College, London. A pioneer in the development of key concepts in the understanding and communication of water issues and how they are linked to agriculture, climate change, economics and politics.	International Elite interview

Annex 3. List of participants in the stakeholder interviews

NAME	TYPE OF STAKEHOLDER	NAME OF INSTITUTION
INTERVIEWS IN SPAIN		
Gerardo Ramos	Academia/Research	Instituto Geológico Minero Español (IGME)
Juan Carlos Muñoz	Business sector	Focus energy, former director of Shale Gas España
Mª Jesús Gallego	Business sector	BNK petroleum
Javier San Román	River Board	Confederación Hidrográfica del Ebro/ Ebro River Basin Organism
Rosa Huertas	River Board	Confederación Hidrográfica del Duero/ Duero River Basin Organism
Víctor Viñuales	Civil Society	ECODES
INTERVIEWS IN THE U.S.		
Michael Paque	Academia/Research	Ground Water Protection Council (GWPC)
Robert Puls	Academia/Research	Oklahoma Water Survey
Kyle Murray	Academia/Research	Oklahoma Geological Survey
William Andrews	Academia/Research	U.S. Geological Survey (USGS)
Nathan Kuhnert	Business	Devon Energy
Mathew E. Mantell	Business	Chesapeake
Rick C. McCurdy	Business	Chesapeake
Brian Woodart	Business	Chesapeake
Derek Smithee	River Board	Oklahoma Water Resources Board
Julie Cunningham	River Board	Oklahoma Water Resources Board

Annex 4. Questionnaire template for Elite interviews

ELITE INTERVIEW

Name:

Profession:

Experience related to water-energy:

A) Introduction to HEREDERA and purpose of the interview

This interview is framed within the Heredera Project, leaded by the Spanish energy company Repsol. Heredera is an ambitious and complex Project that, by means of open innovation and world expert knowledge, aims to model and evaluate the milestones that should be accounted for to foresee the most probable future in related to energy technologies. This way, knowing the key factors which will have an influence in 2020/2030/2050 will enable Repsol to develop a 'complex adaptative system' which helps it adopt an strategic position and become a resilient and competitive company.

In order to undertake this objective, in a first stage a series of interviews to experts in several fields (water, climate change, environment, economy, society, legislation, technology, non natural resources and geopolitics) will be performed, with the aim to reduce the level of uncertainty over variables, trends and key facts. In a second stage, all the experts in the different fields will be invited to participate in a workshop where the Project will be brought to context and all conclusions drawn so far will be presented. Finally, a Real Time Delphi will be conducted so as to build a solid data base.

The purpose of this interview is to know your expert opinion about longterm trends, essential variables and disruptive facts in the field of water, and the main relationships and interconnections with the other fields above mentioned that could influence the energy future. Within the Heredera Project all the information obtained from the interview will be absolutely confidential.

B) Interview

For the interview, you will be asked a series of questions covering different topics which will be recorded by an audio recorder with your permission. It will last for approximately 1 hour and a half, and we will try to adjust to this schedule. This document may serve as a guide for the topics that will be talked through/ addressed, though some questions may be added or omitted depending on the duration of the answers and debates that may arise. Please feel comfortable to ask for a pause or further clarifications about the interview or the questions at any moment.

1. **Population**

World population is expected to grow up to 9,000 million people in 2050. In what aspects will world water demands get affected?

1.1 By 2050, 70% of world population is also expected to live in cities (FAO, 2009; Hoff, 2011). What consequences may this have on water resources and how could they be avoided?

1.2 What could be the implications of a change of diets due to higher incomes in countries like China, India or Brazil?

1.3 The number of people living in regions with severe water stress is expected to grow in the following years. However, different indicators have been used to describe this situation. The most common one is the Falkenmark index (water available per capita), though some authors consider it leaves out some important variables. What is your opinion about this indicator? Would you propose any other instead?

1.4 The Millennium Development Goal of reducing by one half the number of people lacking access to sanitation by 2015 will be unmet by some 13%. Currently about 2.6 billion people lack access to sanitation services. Considering the expected trends on population growth, how do you think will be the evolution of this trend by 2025 and 2050?

2. **Climate change**

2.1 Based on IPCC projections the frequency of droughts is expected to increase in tropical and subtropical regions. What could be the consequences for water management and the energy-food nexus at global scale?

2.2 What could be the expected consequences of climate change scenarios for water availability for crops and crop yields?

2.3 Do you think there could be important regional variations? Where?

3. **Agriculture**

3.1 By 2050, agricultural production will need to be boosted to meet food demands. However, there are different opinions on the role played by rainfed agriculture vs intensive irrigated agriculture. Which do you think could be a more probable scenario by 2050: a considerable increase of rainfed productivity along with a stabilization of irrigated agriculture, or a continued expansion of irrigated agriculture driven by technological advances and productivity improvements?

3.2 Which variables and agents do you think could be marking this situation?

4. **Food**

4.1 Which do you think were the most critical factors driving the increase and volatility of food prices in the last years?

4.2.1 What would be the probability for another rise on the price food and feed commodities impacting global food securities?

4.2.2 Do you think there could be any water factor involved?

4.3 What is the importance and possible evolution of land grabbing?

4.4 What changes in food industry could help face water supply challenges?

5 <u>Economy</u>

Several studies have identified the price of water as one of the critical factors to increase water use efficiency.

5.1 One of the main actions is the implementation of measures for cost recovery in water services. What do you think could be the global and regional evolution of this trend by 2050?

5.2 Do you think the consequent increase on irrigation water prices could challenge food security?

5.3.1 What could be the influence of higher private participation in the financing of water services and infrastructures on their management in the different sectors (agriculture, urban and industry)?

5.3.2 What could be additional or alternative measures?

5.4.1 Do you think there will be an increase on the creation of local-regional water markets in the future?

5.4.2 What could be positive and negative aspects of the implementation?

6 <u>Technology</u>

6.1 It has been observed that water use efficiency policies can drive a rise on consumption, what has been called the 'rebound effect'. How could this problem be faced by water management?

6.2 Currently desalination water plays 0.6% of global water supply, with an annual capacity of 24 km^3. UNESCO expects desalination to be fully competitive by 2040 (WWAP, 2012; IEA-ETSAP et al., 2012).

6.2.1 Do you agree with this prediction?

6.2.2 Which do you think could be the main limiting factors and opportunities related to a future expansion?

6.3.1 According to the Global Water Intelligence, water reuse rates are low. Some examples at local level can be found in the U.S.. 14%; China 14% and Spain 11%. ¿How do you think this rate could evolve by 2030-2050?

6.3.2 In which regions could higher percentages be achieved?

7 <u>Environment-virtual water- cooperation</u>

7.1 What trends can be expected in water management aimed at safeguarding the functionality of ecosystems and their services?

7.2 Water quality degradation and impacts on ecosystems could be exacerbated in regions like India, Pakistan and China due to groundwater overexploitation and intensive use of fertilizers by agriculture (UNEP, 2012). To what extent could this situation constrain water use by other sectors and the environment?

7.3.1 According to some authors (Hoekstra, 2003), virtual water trade will help improve food security in water scarce countries. Do you agree with this vision?

7.3.2 Do you thin countries will tend to increase virtual water trade or rather work to ensure their food provision self-sufficiency?

7.4.1 During the Sixth World Water Forum in Marseille, 2012, representatives of the World Water Council and the World Energy Council agreed to cooperate on issues related to water and energy management efficiency and the building of new dialogues between both sectors. How probable do you think is the actual creation of a global alliance for water and energy?

7.4.2 Do you think this could effectively help to solve water and energy related conflicts?

8. Energy

8.1 How do you think water use by energy will evolve in developed and developing countries?

8.2 International literature diverges in the methodologies used for the estimation of water use for energy (i.e. in terms of withdrawal/consumption or consideration of green and blue water), especially for hydropower and biomass. What aspects do you think should be considered to make these estimations?

8.3 First generation biofuels, this is coming from food crops like maize, soya or wheat, have high water footprints and have a negative impact on food prices. To which extent and when do you think these could be substituted by second and third generation biofuels (energy crops, cellulosic materials, microalgae)?

8.4 Other important water consumers for energy are cooling systems from thermal and nuclear power plants. What technological factors could have higher influence to reduce their impact on water resources?

Annex 5. Delphi Questionnaire: selected variables of uncertainty and questions

5.1. Selected variables of uncertainty and Delphi questions

Variables of uncertainty selected for the Delphi	Delphi questions
Water demands by sector	Indicate the estimated percentage of increase of water withdrawals by sectors1 in 2030 and 2050 compared to 2010
Extent of affection of water stress	Indicate the estimated percentage of global population living under severe water stress conditions (<1,000 m^3/person, year) in 2030 and 2050
Access to sanitation	Indicate the estimated percentage of people connected to sanitation facilities in 2030 and 2050
Wastewater treatment in developing countries	Indicate the estimated percentage or wastewater without treatment in developing countries in 2030 and 2050
Development of alternative water resources in developed and developing countries	Indicate the estimated share in percentage of desalinated water and reuse water in total water supply in developing and developed countries in 2030 and 2050
Global water market	Indicate the estimated growth rate (in %) of global water technologies market by 2030 and 2050
Groundwater degradation	Indicate the estimated groundwater depletion rate by 2030 and 2050
Impacts on water of different energies	Give a score from 1 to 6 according to the importance and magnitude of the impacts of different energy types on water quantity and quality in 2030 and 2050
Shale gas	Give a score from 1 to 6 according to the importance and magnitude of the impacts of shale gas on water quantity and quality
Food prices	Indicate the estimated evolution (in %) of food prices compared to 2010
Cultivated land surface	Indicate the estimated evolution (in %) of cultivated land surface compared to 2012
Consumption patterns	Indicate the estimated evolution (in %) of meat demands compared to 2010

5.2. Format of Delphi questions

The following table shows the final Delphi format taking question 1 as an example.

<table>
<tr><th rowspan="2">Hypothesis and question</th><th>Level of expertise</th><th colspan="2">Your estimation</th></tr>
<tr><td>4 Very high
3 High
2 Low
1 Very low</td><td>2030
%
water for energy
increase</td><td>2050
%
water for energy
increase</td></tr>
<tr><td rowspan="2">Water withdrawals for energy will rise in the following years.

According to the International Energy Agency water withdrawals for energy in 2010 accounted for 583 km^3 (WEO, 2012). This document provides several future scenarios:
Scenario 1: 3% increase by 2035
Scenario 2: 18% increase by 2035
Scenario 3: 36% increase by 2035

Indicate the estimated percentage of increase of water withdrawals for energy in 2030 and 2050 compared to 2010</td><td></td><td></td><td></td></tr>
<tr><td colspan="3">Reasons/ comments</td></tr>
</table>

Annex 6. Questionnaire templates for stakeholder interviews in Spanish and the U.S.

6.1. Questionnaires in Spanish for interviews in Spain

A. Preguntas comunes

Disponibilidad de agua y riesgos

1. ¿Cuáles cree que son los estudios que deberían exigirse a las empresas previa actividad?

2. ¿Cree que el desarrollo y expansión de esta actividad podría afectar a la disponibilidad de agua para otros usuarios, por ejemplo, en el caso de cuencas en que todos los recursos existentes estén ya asignados?

3a. ¿Es posible la utilización de agua depurada procedente de otros sectores como primer input?

3b. ¿Se plantea está opción y su viabilidad a nivel de costes?

4. ¿Cuáles son los principales riesgos de afección a las aguas subterráneas o superficiales que pueden derivarse del proceso de operación o en la fase de abandono?

5. Uno de los posibles riesgos que se ha detectado en Estados Unidos es la migración de metano hacia los acuíferos desde posibles fugas del pozo, o por conexiones con las microfracturas generadas durante la fracturación en la formación confinante (NETL, 2014).

5a. ¿Cree que este riesgo podría darse en el caso de las formaciones españolas?

5b. ¿Qué mecanismos pueden contemplarse para evitarlo o mitigarlo si se diera el caso?

Tratamiento de aguas residuales

6. ¿Qué opciones de gestión del agua producida y el agua de retorno se plantean?

7a. Una solución empleada en Estados Unidos es la inyección profunda de estos efluentes. Sin embargo, se han reportado incidentes de actividad sísmica inducida por esta práctica (Ellsworth, 2013; Davies, 2013).

7b. ¿Cree que esta opción sería factible en España?

8. ¿Es posible la reutilización del agua de retorno y/o el agua producida?

9a. En caso de requerir un cierto tratamiento previo a su reutilización. ¿Qué opciones de tratamiento on-site se consideran?

9b. ¿es viable el coste que esto supone?

10. La necesidad de depuración o gestión alternativa de las aguas residuales con tecnologías avanzadas supone, además del coste de la tecnología en sí, un alto coste energético. ¿Se ha considerado este factor y si resulta asumible?

11. La realización de monitorización y mediciones continuadas durante el desarrollo del proyecto y tras la fase de abandono tienen un coste considerable. ¿Puede este coste suponer una limitación para las empresas o la Administración?

Marco regulatorio

12. ¿Considera que hay algún aspecto en el que la legislación española sea deficiente o insuficiente para regular esta actividad, o que convenga mejorar o desarrollar?

Aceptación social y transparencia

13a. ¿Cómo se plantea el reto de la aceptación social de esta tecnología?

13b. ¿Qué acciones se están llevando a cabo?

14. ¿Cree que la existencia de una plataforma de información al estilo del Frackfocus estadounidense, que favorezca la transparencia, puede influir en la aceptación social de esta tecnología?

15. ¿Es sometido el proyecto en algún momento al trámite de información pública?

B. Preguntas específicas

Academia/investigación

Disponibilidad de información y necesidades de investigación

1. ¿Existe una base de datos nacional con información sobre la cantidad y calidad de los recursos hídricos subterráneos?

2a. ¿Hay alguna iniciativa por parte del IGME para abordar la aparente necesidad de información acerca de los riesgos hidrogeológicos que puede suponer esta actividad y la necesidad de información geológica y evaluaciones geológicas?

2b. ¿Es este segundo punto responsabilidad de las empresas?

3. ¿Cuáles son las principales necesidades de investigación identificadas en relación a la fractura hidráulica y su posible afección a los recursos hídricos?

Empresas

1. Los expertos identifican cuatro procesos clave que será necesario implementar para proyectos de extracción de hidrocarburos por esta técnica de forma segura (Ramos, 2012). Indique si los proyectos contemplan cada uno de estos procesos y/o alguno adicional.

   a) Estudio preoperacional medioambiental hidrogeológico.
   b) Plan de vigilancia ambiental durante el proceso de la actividad con mediciones periódicas.
   c) Plan de emergencias y remediación.
   d) Plan de abandono de sondeos y monitorización.

2. En España son relativamente frecuentes los episodios de sequía en los que puede haber restricciones. ¿Es contemplado este riesgo por las empresas? ¿Cómo se gestiona?

3. Otro riesgo relativamente común en ciertas cuencas es el de inundaciones. ¿Se incluyen estudios de riesgo de inundaciones y planes de actuación?

4. En Estados Unidos se está llevando a cabo investigación en químicos de menor toxicidad para el fluido de fracturación. ¿Se está desarrollando investigación en este sentido en las empresas que pretenden operar en España?

5. Existen líneas de investigación en fluidos de fracturación que emplean otros compuestos distintos del agua como matriz disolvente. Sin embargo, estos materiales son más caros y poseen diferentes propiedades físicas que pueden resultar menos ventajosas para el proceso (Mendez, 2014). ¿Cree que la utilización de estos materiales sustitutivos puede ser una alternativa viable y competitiva en el futuro?

Confederaciones Hidrográficas

1. ¿Cuál es el papel de la Confederación dentro del proceso de evaluación y aprobación de un proyecto de investigación-exploración-explotación de hidrocarburos no convencionales?

2. ¿Qué tipos de controles se plantean exigir a los operadores?

3. La ley de Evaluación de Impacto Ambiental proporciona un procedimiento que establece categorías de impactos. Pero, ¿cree que sería necesario o conveniente establecer un procedimiento estandarizado para todo el territorio español, que incluya indicadores más detallados, para esta actividad específica?

4. En el caso de una actividad que implica un riesgo, como es ésta, el establecimiento de controles e inspecciones de la correcta aplicación de la normativa es de vital importancia

4a. ¿Cómo se plantea la planificación y ejecución de este seguimiento?

4b. ¿Cree que la Administración del Agua tiene capacidad de llevarlo a cabo fehacientemente, con las implicaciones presupuestarias y de trámites administrativos que eso conlleva?

5a. ¿Cómo se contempla el aspecto de la gestión de las aguas residuales?

5b. ¿Cree que las infraestructuras de depuración existentes son capaces de absorber los efluentes generados en esta actividad, por ejemplo en el caso de su Confederación?

6. ¿Se definirán unos criterios de calidad específicos para los efluentes de esta actividad, o se regirán por los parámetros establecidos para aguas industriales?

7. ¿Cuáles son las principales incertidumbres y problemas que se encuentra la Administración del Agua a la hora de enfrentar la regulación de la interacción y efectos de esta actividad sobre los recursos hídricos?

Sociedad civil

1. ¿Cuál es la posición o papel que están intentando adoptar las organizaciones de la sociedad civil frente al debate existente?

2. ¿Estima que hay información de calidad disponible y accesible para la sociedad?

3. ¿Considera que esta disponibilidad de información puede influir en la posible aceptación social de esta tecnología?

4. ¿Cuáles son los factores relativos a las posibles afecciones del fracking a la calidad del agua documentadas que generan mayor preocupación en la organización?

5a. ¿Qué papel cree que deben jugar las administraciones del agua (Confederaciones) para asegurar la protección de las aguas?

5b. ¿Hay alguna actuación en particular que cree que se deberían promover?

6. ¿Cree que la necesidad de mejoras en las infraestructuras de tratamiento de aguas que implicaría el desarrollo de estos proyectos puede ser una oportunidad o una carga financiera?

7. ¿Cree que deberían correr por cuenta del Estado o de las empresas operadoras?

6.2. Questionnaires in English for interviews in the U.S.

A. Common questions

Water availability related risks

1. How are water demands met when water available is scarce or during drought periods?

2. What are the main water sources currently used for hydraulic fracturing operations?

3a. Are alternative water resources (urban or industrial waste water reuse) considered as an option?

3b. Is this option economically viable?

Wastewater management

4a. How is wastewater management usually carried out?

4b. Are there any regulations in this respect?

5. Could the increase on earthquake frequency and intensity registered in the last years in some areas (e.g. Oklahoma) as a result of deep well injection of hydraulic fracturing wastewater lead to supra state considerations of banning this practice as a matter of public security?

6. Is hydraulic fracturing the only activity that uses this method for wastewater disposal?

7. What is the final destination of treated wastewater?

8. Is there any regulation and tracking of wastewater discharges into water bodies? What is the institution responsible for these aspects?

9. What are the main pollutants that need to be removed?

Costs

10. Besides the purchasing cost of the technology, onsite wastewater treatment entails additional costs for the use of energy. Are these costs a relevant factor within the final cost?

11. How can the implementation of measuring and monitoring processes impact the final cost?

Transparency and social acceptance

12. What are people's main concerns in relation to fracking?

13. Have the frackfocus platform and the willingness of O&G companies to increase transparency affected the social acceptance of HF in the different states?

14. Are HF projects subject to public consultation processes at any stage?

Regulatory aspects

15. Is there any initiative or intention to produce specific legislation at federal level to unify criteria?

16. a What kind of studies or previous documentation are O&G companies required to provide in order to be issued an exploration and exploitation permission in Oklahoma?

16.b Are there any substantial differences with other states or the requirements tend to be similar?

B. Specific questions

Academia/research

Data availability and research needs

1. Is there a national database on groundwater resources that includes information on the quantitative and qualitative state of the aquifers?

2. Are there any initiatives from the USGS/GWPC intending to deal with the apparent need of baseline data and information on the conditions of groundwater or is it supposed to be something that the operator or the owner of a well should do?

3. What are the main research needs identified in relation to hydraulic fracturing and water resources?

Business

1. What strategies are companies considering to face the risk of a reduction on water availability due to drought periods or an unsustainable increase of water demand for oil and gas in the future?

2a. Are oil and gas companies currently doing any water discharges to the rivers?

2b. If so, are there any inspection or monitoring systems and regulations for these discharges?

3. Some companies are developing advanced fluids made of gels, CO_2, He or other non-water components, which are proving high fracturing efficiencies and favorable properties. Can these fluids become an economically viable option for hydraulic fracturing in water stressed areas?

4. How would the flow back fluid waste be managed in this case?

5. How are companies facing the challenge of the social acceptance of this technology?

River Boards

1. Is oil and gas applied the same rules than other types of industry?

2. What are the criteria for the RBO to decide whether a hydraulic fracturing project should be granted a water permit?

Annex 7. Questionnaire template for expert interviews and online survey

SECTION A: KEY DRIVERS AND TRENDS FOR THE FUTURE ON THE WATER-ENERGY-FOOD NEXUS

Question 1. What are - in your opinion - the critical drivers or trends related to the water-energy-food nexus that could have higher impacts in the short- term and would need priority attention?

Question 2. What are in your opinion the weakest points or main knowledge gaps related to the water-energy-food nexus?

Question 3. Here is a list of tools that could help address the WEF nexus and climate change related impacts. Could you assign them a value from 1 to 4 based on their potential relevance, 1 being the lowest importance and 4 the highest importance?

1. Life cycle analysis [1 2 3 4]
2. Integrated modeling (including life and social sciences) [1 2 3 4]
3. Qualitative tools in the nexus (participatory approaches, scenario thinking, expert panels, …) [1 2 3 4]
4. Data collection and management [1 2 3 4]
5. Communication and Capacitation [1 2 3 4]
6. Stewardship approaches (value based) [1 2 3 4]
7. Piloting, implementation and testing-monitoring [1 2 3 4]
8. Risk assessment and multi-strategy planning [1 2 3 4]
9. Spatial tools, mapping, guiding models [1 2 3 4]
10. Weather control and forecasting tools [1 2 3 4]
11. Regulation as a driver for innovation [1 2 3 4]
12. Pricing and economic instruments [1 2 3 4]
13. Other (specify)

SECTION B: EMERGING PRIORITIES FOR FUTURE RESEARCH AND INNOVATION IN TECHNOLOGIES AND SOCIAL APPROACHES. POTENTIAL DISRUPTIVE SIGNALS AND EVENTS.

WATER FOR ENERGY

Question 4. Which do you think are the key drivers that will lead the technological and social research roadmaps for the future in the water for energy nexus?

Question 5. Of the list of main topics below: how would you rank them (1 to 4, 1 being the least important, and 4 the most important)

1. Ageing water and energy infrastructure [1 2 3 4]
2. Transitioning systems [1 2 3 4]
3. High efficiency – low water consuming cooling systems [1 2 3 4]
4. Hydro-wind energy integration [1 2 3 4]
5. New generation biofuels [1 2 3 4]
6. Hydraulic pumping Energy storage (as key for renewables take off) [1 2 3 4]
7. Alternative fluids for drilling and as heat exchange vectors [1 2 3 4]
8. Evaporation control [1 2 3 4]
9. Integrated water-energy modeling [1 2 3 4]
10. Self-generation (e.g. solar or wind) e.g. solar pumping [1 2 3 4]
11. Processes generating water as by product [1 2 3 4]
12. Other (specify)

ENERGY FOR WATER

Question 6. Which do you think are the key drivers to lead the technological and social research roadmap for the future in the energy for water nexus?

Question 7. Of the list of main research lines below how would you rank them (1 to 4, 1 being the least important, and 4 the most important)

1. Coupled renewables-desalination. New desalination technologies (membranes) [1 2 3 4]
2. Water conservation systems [1 2 3 4]
3. Use of nanotechnologies to improve efficiency and technological innovation [1 2 3 4]
4. Water re-use and recycling [1 2 3 4]
5. Carbon and water footprints [1 2 3 4]
6. Resource recovery systems along the water cycle (energy, nutrients) [1 2 3 4]
7. Other (specify)

WATER ←→ FOOD

Question 8. Which do you think are the key drivers to lead the technological and social research roadmap for the future in the water ←→ food nexus?

Question 9: Of the list of main research lines below how would you rank them (1 to 4, 4 being the least important, and 4 the most important)

1. Productivity of rain-fed irrigation [1 2 3 4]
2. Saline crops [1 2 3 4]
3. Treated wastewater reuse in irrigation [1 2 3 4]
4. Productivity gap e.g. in Africa (driving research in productivity [1 2 3 4] improvements)
5. Aeroponic crops (rapid growth crops requiring little water and soil) as an alternative for traditional biofuels [1 2 3 4]
6. Virtual water and water savings [1 2 3 4]
7. Crop intensification [1 2 3 4]
8. Crop extensification [1 2 3 4]
9. Urban agriculture [1 2 3 4]
10. Rapid growth plants [1 2 3 4]
11. Remote sensing; capture of real time data (GPS, ICTs) [1 2 3 4]
12. Biotechnology and genetic engineering [1 2 3 4]
13. Other (specify)

ENERGY ←→ FOOD

Question 10. Which do you think are the key drivers to lead the technological and social research roadmap for the future in the energy ←→ food field?

Question 11: Of the list of main research lines below how would you rank them (1 to 4, 4 being the least important, and 4 the most important)

1. Improvement of energy efficiency in food industry [1 2 3 4]
2. Production of artificial meat in laboratory [1 2 3 4]
3. Production of vegetal/plant proteins meat [1 2 3 4]
4. GMOs and plant breeding to reduce water footprint, increase resilience and reduce competence with food of bioenergy [1 2 3 4]
5. Resource efficiency in the whole supply chain [1 2 3 4]
6. Sustainable food consumption and production [1 2 3 4]
7. Behavioral change of consumers [1 2 3 4]
8. Management/reuse of food waste [1 2 3 4]

9. Use of Information and Communication Technologies for resource efficiency [1 2 3 4]
10. Other (specify)

FINAL QUESTIONS:

Question 12. What do you think could be disruptive events (events that can lead to a drastic change on the general trendlines) affecting the nexus?

Water-energy

Food –water

Energy-food

Question 13. Do you think all of the axes have the same importance or is there anyone that in your opinion should be prioritized? Justify your answer.

Question 14. What role could climate change play in the nexus? Please justify your answer

You are welcome to provide any additional comments or suggestions

Thank you for your time!!

Annex 8. Metrics for large and small scale hydropower

8.1. Metrics for large scale hydropower plants

LARGE SCALE HYDROPOWER										
Plant	Capacity (MW)	Maximum flow (m3/s)	Annual production (Mwh)	Hydraulic Pumping Capacity	Reservoir	Reservoir capacity (hm3)	Reservoir surface (m2)	Lenth of river stretch (m)	Water withdrawal (m3)	Evaporation (m3)
Agavanzal	24.09	60.00	52,210.00	NO	Agavanzal	35.90	3,650,000.00	17,446.00	468,115,063.72	3,034,000
Aguilar de Campoo	10.23	24	20,600.00	NO	Aguilar de Campoo	247.23	16,460,000.00	15,000	173,982,404.69	7,440,000
Aldeávila I	855.00	625.80	2,480,700.00	NO	Aldeávila	114.87	4,060,000.00	42,287	6,536,513,936.84	4,330,000
Aldeávila II	408.00	340.00	195,000.00	YES	Aldeávila	-----	-----	1,000.00	585,000,000.00	-----
Camporredondo	14.77	22.00	26,698.12	NO	Camporredondo	69.79	4,052,000.00	15,038	143,141,807.96	1,290,000
Castro I	87.58	270.00	221,156.40	NO	Castro	27.50	1,573,000.00	25,558.00	2,454,375,465.84	1,860,000
Castro II	120.20	340.00	300,000.00	NO	Castro	-----	-----	900.00	3,054,908,485.86	-----
Cernadilla	30.00	60.00	55,900.00	NO	Cernadilla	255.54	13,419,000.00	39,411.00	402,480,000.00	8,424,000
Compuerto	20.00	24.00	51,700.00	NO	Compuerto	95.00	3,807,300.00	21,514.00	223,344,000.00	1,160,000
La Remolina	85.00	106.00	97,630.00	NO	Riaño	651.14	20,679,000.00	42,600.00	438,301,270.59	6,940,000
Moncabril	35.96	8.00	91,320.44	NO	Porto & Playa	25.88	2,766,000.00	17,187.00	73,137,612.01	1,515,768
Porma	16.60	30.00	62,800.00	NO	Porma	317.83	11,825,200.00	29,245.00	408,578,313.25	6,940,000
Ricobayo I	183.30	240.00	684,000.00	NO	Ricobayo	1,178.88	59,179,900.00	164,775.00	3,224,091,653.03	31,890,000
Ricobayo II	135.00	210.00	130,000.00	NO	Ricobayo	-----	-----	329.00	728,000,000.00	-----
San Isidoro	38.40	40.80	62,100.30	NO	Barrios de Luna	308.00	11,300,000.00	40,000.00	237,533,647.50	5,240,000
Santa Teresa	19.88	50.00	69,950.00	NO	Santa Teresa	496.00	26,239,200.00	37,360.00	633,350,100.60	16,240,000
Saucelle I	285.00	475.20	600,000.00	NO	Saucelle	181.37	6,031,000.00	31,935.00	3,601,515,789.47	7,340,000
Saucelle II	252.00	523.00	488,000.00	NO	Saucelle	-----	-----	1,501.00	3,646,057,142.86	-----
Valparaíso	60.00	158.00	60,000.00	YES	Valparaíso	162.37	12,559,000.00	49,180.00	568,800,000.00	10,354,000
Villalba	12.60	17.00	52,000.00	NO	Velilla de Guardo	1.81	290,000.00	14,440.00	252,571,428.57	204,000
Villalcampo I	96.00	303.00	119,520.00	NO	Villalcampo	66.00	2,253,000.00	22,400	1,358,046,000.00	4,140,000
Villalcampo II	110.00	340.00	137,000.00	NO	Villalcampo	-----	-----	573	1,524,436,363.64	-----
Villarino-Almendra	829.75	232.50	1,930,000.00	YES	Almendra	2,586.34	84,615,300.00	122,600.00	1,946,863,513.11	50,520,000
TOTAL	**3,729.37**	**4,499.30**	**7,988,285.25**			**6,821.46**	**284,758,900.00**	**752,279.00**	**32,683,143,999.54**	**168,861,768**

8.2. Metrics for small scale hydropower plants

SMALL SCALE HYDROPOWER											
Plant	**Type**	**Capacity (kW)**	**Maximum flow (m3/s)**	**Annual production (kwh)**	**Hydraulic Pumping Capacity**	**Reservoir**	**Reservoir capacity (hm3)**	**Reservoir surface (m2)**	**Lenth of river stretch (m)**	**Water withdrawal (m3)**	**Evaporation (m3)**
Acera de la Vega	Canal	8,670	17	34,200,000	NO	Small dam	1.80	290,000	11,350	241,411,764.71	177,190
Agueda	RHP	4,980	20	9,840,000	NO	Agueda Reservoir	22	1,770,000	13,333	142,265,060.24	1,610,000
Aguilarejo	RoR	1618	60	5,693,267	NO	weir	------	------	33.28	760,040,588.38	
Alar	RoR	406	20	1,642,871	NO	weir	------	------	370	291,346,581.28	
Alcoba de la Ribera o Alcoba	canal	9,600	38	23,190,000	NO	weir	------	------	9,400	330,457,500.00	
Alcozar	RoR	4480	30	2,826,068	NO	weir	------	------	150	68,128,425.00	
Almenara	RoR	402	14	1,620,041	NO	Small dam	------	14,300	528	195,855,702.99	5,220
Ambasaguas de Curueño	RoR	1,990	9	5,969,643	NO	weir	------	------	4436	99,354,058.37	
Aranda I	RoR	184	8	2,848,679	NO	weir	------	------	115	445,880,191.30	
Aranda II	RoR	500	20	2,465,657	NO	weir	------	------	107	355,054,608.00	
Arlanzón	RHP	1,200	4	4,463,000	NO	Arlanzón Reservoir	23.38	1,274,400	2,366	53,556,000.00	660,000
Arroyo de Los Pozos	RoR	1,074	0	706,692	NO	weir	------	------	1,384	592,200.00	
Ausin o Molino de Ausin	RoR	1,882	60	5,455,394	NO	weir	------	------	266	626,123,859.72	
Barrios de Luna	RHP	400	1	2,515,200.00	NO	Barrios de Luna Reservoir	0.31	11,300,000	17460	11,318,400.00	5,240,000
Bocos	RoR	1438	30	3,517,436	NO	weir	------	------	50	264,174,609.18	
Boñar I o Boñar	RoR	2,434	18	12,290,000	NO	weir	------	------	3,650	327,194,741.17	
Bubones	RoR	1468	20	3,209,352	NO	weir	------	------	2,000	157,406,910.08	
Burgomillodo	RHP	3233	9	3,588,586	NO	Burgomillodo Reservoir	15.00	940,000	9569	36,562,951.70	930,000
Camposolillo	RoR	1,700	10	2,507,328	NO	weir	------	------	1,369	53,096,357.65	
Canal de Almazán	RoR	1,576	14	1,822,436	NO	weir	------	------	79	58,280,948.22	
Casares	RoR	1,970	3	2,920,000	NO	Casares Reservoir	37.00	2,800,000	3,010	16,008,121.83	1,770,000
Castro de Las Cogotas o Las Cogotas	RHP	5,251	10	13,800,000	NO	Las Cogotas Reservoir	58.60	4,000,000	8,630	94,610,550.37	2,362,000
Cimanes del Tejar o Cimanes	canal	9,600	38	25,560,000.00	NO	weir	------	------	9,600	364,230,000.00	
Cubo de Don Sancho	RoR	49	20	65,817	NO	Small dam	------	35,000	300	96,710,693.88	
Cuerda del Pozo	RHP	6,035.20	21	8,500,000	NO	Cuerda del Pozo Reservoir	229.00	21,760,000	21,760	103,940,217.39	11,000,000
El Chorro	RoR	1,024	1	4,230,000	NO	El Duque Reservoir	2.50	270,000	1,846	13,383,984.38	117,180
El Cabildo	RoR	606	27	1,867,624	NO	weir	------	------	180	296,408,570.99	
El Cardiel	RoR	260	6	782,457	NO	weir	------	------	470	65,004,120.00	
El Hoyo	RoR	3,582	105	5,867,695	NO	weir	------	------	1,410	619,203,994.97	
El Martinete	RoR	639	4	758,493	NO	weir	------	------	682	17,092,800.00	
El Pisón	RoR	75	3	94,114	NO	weir	------	------	377	11,438,239.10	
El Tejado	RoR	662	24	2,517,349	NO	weir	------	------	295	328,548,268.28	
El Vergueral	RoR	515	20	42,224,080	NO	weir	------	------	450	5,903,172,349.51	
Esclusa 14 Canal Castilla o Esclusa 14	canal	237	8	950,000	NO	canal	------	------	124	112,556,962.03	
Esclusa 38	canal	60	2	400,396	NO	canal	------	------	76	47,567,044.80	
Esclusa cuatro o La Cuarta	canal	70	1	441,396	NO	canal	------	------	76	22,700,365.71	
Espinosa de la Ribera o Espinosa	canal	9,780	38	16,325,378	NO	weir	------	------	7,000	228,354,975.48	
Ferreras	RoR	2,434	4	10,400,000	NO	Transfer	------	------	30,000	61,528,348.40	
Frómista (Esclusa 17, 18, 19 y 20)	canal	789	2	2,367,000	NO	canal	------	------	306	21,600,000.00	
Fuentermosa o Fuentehermosa	RoR	348	1	1,008,667	NO	weir	------	------	600	13,043,107.76	
Garrido	RoR	128	2	66,167	NO	Bodón de la Ibienza Reservoir	Rep.	Rep.	400	3,766,556.48	
Gormaz	RoR	415	18	608,096	NO	weir	------	------	500	94,950,893.49	
Guma	RoR	2,295	35	7200000	NO	Small dam	0.89	188,050	3,000	395,294,117.65	85,187

Herreros	RoR	1,208	101	7,049,200	NO	weir	------	------	270	2,119,661,761.59	
Husillos	RoR	329	15	924,000	NO	weir	------	------	550	151,659,574.47	
La Aurora	RoR	656	25	1,284,904	NO	weir	------	------	331	176,282,560.98	
La Conchita	RoR	848	36	2,229,852	NO	weir	------	------	97	340,788,701.89	
La Confianza	RoR	640	6	796,004	NO	Small dam	12.40	4,380	284	26,865,135.00	1,353
La Flecha	RoR	984	85	8,045,099	NO	Small dam	------	20,140	55	2,501,829,567.07	5,518
La Gila	RoR	76	3	456,000	NO	weir	------	------	49	64,238,400.00	
La Güera	RoR	132	4	224,462	NO	weir	------	------	223	24,486,763.64	
La Higuerilla	RoR	580	17	1,445,051	NO	weir	------	------	337	152,477,795.17	
La Isla	RoR	1,884	118	7,748,222	NO	weir	------	------	252	1,747,791,605.92	
La Josefina	RoR	1,112	36	2,920,119	NO	weir	------	------	447	340,330,415.83	
La Lera	RoR	408	15	1,581,679	NO	weir	------	------	1,087	209,339,867.65	
La Pelotera	RoR	246	0	746,300	NO	weir	------	------	758	40,955.49	
La Peña o Villahoz	RoR	432	11	1,173,200	NO	weir	------	------	200	111,454,000.00	
La Pola de Gordón	RoR	425	11	704,822	NO	weir	------	------	172	64,478,774.96	
La Rachela	RoR	290	4	930,900	NO	weir	------	------	625.6	46,224,000.00	
La Recorba	RoR	432	12	25,415.65	NO	Small dam	------	200	40	2,541,565.00	86
La Requejada	RHP	4,217	10	13,621,339	NO	La Requejada Reservoir	66.42	3,330,000	9,360	118,609,335.57	1,350,000
La Ventosa	RoR	110	7	0	NO	weir	------	------	829	34,821,818.00	
La Villa o Salto de la Villa	RoR	421	8	1,139,909	NO	weir	------	------	800	77,979,523.04	
Las Arenillas o Fuenrosario	RoR	76	4	547,500	NO	weir	------	------	121	114,110,526.32	
Las Once Paradas	RoR	224	9	600,423	NO	weir	------	------	583	82,022,070.54	
Las Sorribas	RoR	208	8	5,600,000	NO	weir	------	------	5,500	38,304,000.00	
Las Vencias	RHP	2,400	15	1,840,335	NO	Las vencias reservoir	9.00	580,000	5,200	41,407,537.50	610,000
Ligüérzana	RoR	500	12	1,780,070	NO	weir	------	------	168	153,798,048.00	
Linares del Arroyo	RHP	1,604	7	2,450,000	NO	Linares del Arroyo Reserovoir	54.55	4,700,000	9,900	38,491,271.82	3,830,000
Los Cotriles	RoR	306	5	1,779,696	NO	weir	------	------	607	94,219,200.00	
Los Leones o Puente de los Leones	RoR	674	20	1,186,384	NO	weir	------	------	10	126,735,382.79	
Los Molinos del Soto o Los Molinos	RoR	733	9	4,300,000	NO	weir	------	------	1,000	185,844,474.76	
Los Rábanos	RHP	4,480	30	4,800,435	NO	Los Rábanos Reservoir	6.40	920,000	6,836	115,724,772.32	750,000
Lubián I o Salto de Lubián	RoR	1,070	3	2,025,860	NO	canal	------	------	1,464	20,938,683.10	
Lugán	RoR	846	5	2,951,173	NO	weir	------	------	3,050	62,790,914.89	
Maire	RoR	430	12	1,696,390	NO	weir	------	------	3,565	170,428,018.60	
Matallana de Torío o Torío I	RoR	1,520	12	2,680,845	NO	Small dam	0.50	------	1,233	76,192,436.84	
Matazorita	RoR	210	6	1,256,059	NO	weir	------	------	1,233	129,194,640.00	
Molinaferrera	RoR	1,244	1	2,043,174	NO	weir	------	------	1,100	7,390,902.73	
Molino de Andrés	RoR	3,750	22	4,046,280	NO	Small dam	0.84	114,200	56	85,457,433.60	62,239
Molino de Getino	RoR	107	4	332,388	NO	weir	------	------	67	44,732,590.65	
Molino de Las Huertas	RoR	330	20	1,221,935	NO	weir	------	------	932	266,604,000.00	
Molino del Batán o Los Batanes	RoR	220	3	269,459	NO	weir	------	------	156	13,227,987.27	
Molino del Puente	RoR	404	20	1,453,139	NO	weir	------	------	510	258,975,267.33	
Molino El Berral o El Berral	RoR	148	2	239,710	NO	weir	------	------	806.8	9,399,223.46	
Molino Rica Posada	RoR	8	1	24,000	NO	weir	------	------	273	5,918,400.00	
Molino San Andrés	RoR	33	1	111,355	NO		------	------	2942	10,896,592.91	
Molinos de Castilla	RoR	1,872	32	4,997,734	NO	weir	------	------	172	309,378,956.65	
Monasterio	RoR	1,366	40	3,240,110	NO	weir	------	------	20	341,563,572.47	
Morla	RoR	188	2	575,612	NO	small dam	------	9,600	2,000	22,044,714.89	4,147
Navapalos	RoR	542	20	2,244,958	NO	small dam	------	37,000	507.5	298,223,202.95	17,797
Nuestra Señora de las Mercedes	RoR	2,020	70	7,296,723	NO	small dam	0.06	135,750	1,100	910,284,255.45	46,698
Peña Corada	RoR	4,990	63	14,389,836	NO	small dam		28,000,000	1270	652,992,878.53	10,136,000
Pereruela	RoR	3,160	75	11,788,000	NO	San Román Reservoir	1.50	1,250,000	3,853	1,007,202,531.65	1,250,000