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Doctoral Thesis in Energy and Environmental Systems

Energy-Water and Agriculture Nexus to Support the Sustainable Management of Shared Water Resources

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Stockholm, Sweden 2023

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Abstract

Throughout history, major rivers and shared water bodies have allowed civilizations to flourish, and the effective management of shared water bodies has always been a priority for societies and nations. Today, about 40% of the world's population lives in proximity to the 286 transboundary river and lake basins that supply 60% of the world's freshwater flows and make up about half of the Earth's land area. Moreover, around 2 billion people in the world depend on groundwater sources, which include over 460 transboundary aquifer systems.

The mismanagement of water resources can result in catastrophic disasters that are often exacerbated by a domino effect so that the impacts of poor water management often extend beyond the water system. The interdependency of the water system with other systems such as energy and food, or with land-use, highlights the importance of ”systems thinking and planning” in resource management. Such a concept is not easily encapsulated into policy-making processes in many parts of the world because consideration of the resource systems in isolation as individual entities and 'silo” thinking still dominate. Climate change adds another layer of complexity and exacerbates the issue of water management. Another important factor is geographical location because precipitation varies among and within continents. This results in some regions suffering from water shortages and some regions facing the risks of water redundancy and floods.

The concept of the Water-Energy-Food (WEF) nexus was introduced in 2011 as a response to help address some of the issues mentioned above. Over the last decade, research on the WEF nexus has gained momentum in both the policy and academic areas and several methods have been introduced to operationalize the nexus in different contexts. One of the flagship methodologies is the Transboundary Basins Nexus Approach (TBNA) introduced by the United Nations Economic Commission of Europe (UNECE) in 2015 and designed to assess the nexus in shared (transboundary) water basins.

The aim of this thesis is to support shared water management by using the WEF-nexus approach to quantify the benefits of coordinated management, motivate cooperation, and identify trade-offs in the optimal use of resources. To achieve this aim, four research questions are explored over the course of four academic publications.

The first question explores the role of the energy sector in motivating shared water cooperation. The second question studies the risks and opportunities emerging from the interplay between climate and renewable energy in shared basins. The third question focuses on groundwater management and explores what benefits the consideration of the energy-water-agriculture nexus could bring to shared groundwater management in water-scarce areas. The fourth question examines how consideration of the energy-water-agriculture nexus could accelerate the low-carbon transition in the agricultural sector.

These research questions are examined in two different, yet complementing, geographic locations. One is the Balkans in Southeastern Europe, which faces water redundancy and flood issues and the other is the Middle East and North Africa (MENA) region which suffers from water scarcity. In the first region, the Drina and the Drin River Basins represent the characteristics of Southeastern Europe while the North Western Sahara Aquifer System (NWSAS) and the Souss-Massa basin represent the characteristics of the MENA region. Three of the case applications are transboundary (Drina, Drin and NWSAS) while the last application (Souss-Massa Basin) is a subnational basin.

Keywords: shared water management; WEF nexus; agriculture, water and energy systems; hydropower; climate change; groundwater.

Sammanfattning

Historiskt har stora floder och delade vattendrag gjort det möjligt för civilisationer att blomstra. Att effektivt hantera delade vattenresurser har alltid varit och är en prioritet för samhällen och nationer. Idag bor cirka 40 % av världens befolkning i nära anslutning till någon av de 286 internationella floder och sjöar som är just delade vattendrag. De försörjer 60 % av världens sötvatten och utgör ungefär hälften av jordens yta. Vidare är omkring 2 miljarder människor i världen beroende av grundvattenkällor, som inkluderar över 460 gränsöverskridande akvifera system.

Dålig vattenförvaltning kan leda till katastrofala följder med efterföljande dominoeffekt där dålig vattenförvaltning inte bara påverkar vattensystemet, utan även andra relaterade system så som energi, mat och markanvändning. Vattensystemets ömsesidiga beroende av andra system understryker vikten av "systemtänkande och planering" i resurshantering. I många delar av världen domineras dock policyprocesserna av att se resurssystemen som isolerade individuella enheter, ett så kallat "silo"-tänkande. Klimatförändringarna lägger till ytterligare ett lager av komplexitet till frågan om vattenförvaltning. Det geografiska läget har också betydelse eftersom den globala nederbörden varierar mellan och inom kontinenter. Detta resulterar i att vissa regioner lider av vattenbrist och andra riskerar att få vattenöverflöd och bli översvämmade.

Konceptet vatten-energi-mat (WEF)-nexus introducerades 2011 som en lösning för att hjälpa till att ta itu med några av de ovan nämnda problemen. Forskningen kring WEF-nexus tog fart under det efterföljande decenniet, både inom politiska och akademiska arenor, och flera metoder introducerades för att göra nexus användbart i olika sammanhang. En av flaggskeppsmetoderna är Transboundary Bassins Nexus Approach (TBNA) som introducerades av FN:s ekonomiska kommission för Europa (UNECE) 2015 och är utformad för att förstå och utvärdera delade (gränsöverskridande) vattenavrinningsområde.

Denna avhandling syftar till att stödja delad (gränsöverskridande) vattenförvaltning genom att använda WEF-nexus-metoden till att kvantifiera fördelarna med samordnad förvaltning, motivera samarbete samt identifiera avvägningar i optimal användning av resurser. Detta undersöks genom fyra forskningsfrågor och redovisas i fyra publikationer.

Den första frågan utforskar energisektorns roll i att motivera delad vattenförvaltning och vilka insikter som kan erhållas från modeller med öppen källkod. Den andra frågan studerar riskerna och möjligheterna av samspelet mellan klimat och förnybar energi i delade vattenavrinningsområden. Den tredje frågan fokuserar på grundvattenhantering och undersöker vilka fördelar systemtänkande kring energi-vatten-jordbruk kan ge till delad grundvattenhantering i områden med vattenbrist. Den fjärde frågan undersöker hur hänsynstagandet till sambandet energi-vatten-jordbruk kan påskynda omställningen med låga koldioxidutsläpp inom jordbrukssektorn.

Dessa forskningsfrågor undersöks på två olika, men kompletterande, geografiska platser. Den ena är Balkanregionen i sydöstra Europa, som står inför översvämningsproblem, och den andra är Mellanöstern- och Nordafrika-regionen (MENA) som lider av vattenbrist. I den första regionen representerar floderna Drina och Drin några av särdragen för sydöstra Europa, medan North Western Sahara Aquifer System (NWSAS) och Souss-Massa-vattenavrinningsområde representerar särdrag i MENA-regionen. Tre av fallstudierna är gränsöverskridande (Drina, Drin och NWSAS) medan den sista studien (Souss-Massa Basin) är ett nationellt vattenavrinningsområde.

Nyckelord:

Delad vattenförvaltning; WEF-nexus; jordbruk, vatten och energisystem; vattenkraft; klimatförändring; grundvatten.

خلاصة

لعبت الأنهار الرئيسية والمسطحات المائية المشتركة دورا محوريا في ازدهار الحضارات على مر التاريخ ، وشكلت الإدارة الفاعلة للمسطحات المائية المشتركة أولوية كبرى للأمم والمجتمعات، وفي الوقت الراهن يعيش حوالي 40٪ من سكان العالم بالقرب من أحواض الأنهار و البحيرات العابرة للحدود البالغ عددها 286 حوضا مشتركا، والتي تغطي حوالي نصف مساحة اليابسة وتشكل المصدر الرئيسي لـ 60٪ من تدفقات المياه العذبة في العالم. علاوة على ذلك، يعتمد حوالي 2 مليار نسمة في العالم على مصادر المياه الجوفية النابعة من 460 نظامًا لطبقات المياه الجوفية العابرة للحدود.

إن سوء إدارة الموارد المائية يمكن أن يؤدي إلى كوارث متعددة الأبعاد غالبًا ما تتجاوز منظومة المياه، كما أن الترابط بين النظام المائي والأنظمة الأخرى مثل الطاقة والغذاء (أو استخدام الأراضي) يسلط الضوء على أهمية "التفكير والتخطيط النظمي" في إدارة الموارد، وهو مفهوم لا يمكن ترجمته بسهولة في عملية صنع السياسات في أجزاء كثيرة من العالم، حيث لا يزال التفكير والتخطيط الأحادي والمنعزل لأنظمة الموارد هو المسيطر.

التغير المناخي يضيف بدوره مستوى آخر من التعقيد ويفاقم من أزمة إدارة المياه، والعامل الأخر المهم هو الموقع الجغرافي حيث تتباين مستويات هطول الأمطار بين القارات وفي داخلها، مما انعكس على تباين تحديات المياه حول العالم، ففي حين نجد بعض المناطق تعاني من شح الموارد المائية، نجد مناطق أخرى تعاني من مخاطر وفرة المياه والفيضانات.

ظهر مفهوم "الترابط بين المياه والطاقة والغذاء (WEF-nexus)" في عام 2011م كمساهمة في معالجة بعض القضايا المذكورة أعلاه، وخلال العقد الماضي اكتسب البحث حول "الترابط بين الماء والطاقة والغذاء" زخمًا كبيرا في المجال الأكاديمي وكذلك في مجال صنع السياسات التنموية، وتم ابتكار العديد من النماذج التطبيقية لاسقاط مفهوم التفكير الترابطي بين الموارد على أرض الواقع وتطبيقه في سياقات مختلفة، إحدى المنهجيات الرئيسية هي منهجية الترابط في الأحواض العابرة للحدود (TBNA)، والتي ابتكرتها اللجنة الاقتصادية لأوروبا التابعة للأمم المتحدة (UNECE) في عام 2015 لتقييم الترابط بين الموارد في أحواض المياه المشتركة (العابرة للحدود).

تهدف هذه الأطروحة إلى دعم إدارة المياه المشتركة باستخدام نهج "الترابط بين المياه والطاقة والغذاء WEF-nexus" وذلك من خلال الدراسة الكمية لفوائد الإدارة التكاملية للموارد، وتحفيز التعاون بين الشركاء، ودراسة التبعات أوالمقايضات في الاستخدام الأمثل للموارد، ولتحقيق هذا الهدف؛ تمت دراسة أربعة أسئلة بحثية عبر أربعة أبحاث علمية محكمة.

يبحث السؤال الأول دور قطاع الطاقة في تحفيز التعاون في مجال المياه المشتركة، في حين يبحث السؤال الثاني المخاطر والفرص الناتجة من التفاعل بين المناخ ومصادر الطاقة المتجددة في الأحواض المشتركة، أما السؤال الثالث فيركز على إدارة المياه الجوفية ويستكشف الفوائد التي يمكن أن تجلبها دراسة "الترابط بين الطاقة والمياه والزراعة" في إدارة المياه الجوفية المشتركة وبالأخص في المناطق التي تعاني من شح الموارد المائية، أما السؤال الرابع فيدور

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الكلمات المفتاحية: إدارة المياه المشتركة ؛ الترابط بين الموارد المائية و الطاقة والغذاء؛ أنظمة الطاقة؛ الطاقة الكهرومائية؛ تغير المناخ؛ المياه الجوفية.

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Looking at my schedule to check the next lecture of my master studies while asking myself how can I drop this course! Running late and entering a big lecture hall full of students; I ended up standing at the back. The speaker soon starts his first lecture of the ‘*Energy and Environment*’ course and it was a ‘wow’! After the first inspiring lecture with Prof. Mark Howells, I ended up checking how to enrol in his next course! And here I am, several years after that lecture, wrapping up this very long but rewarding PhD journey.

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Thank you all for being part of this story ...

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Stockholm, 4th January 2023

للنجوم المتلألأة في سماء الغربة ...

و للنفوس الراسخة رغم طول الرحلة ...

أهدي لكم هذه الرسالة ...

مع خالص المودة والمحبة ...

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UNECE

Food and Agriculture Organization of the United Nations

UN DESA

Global Water Partnership Mediterranean

DRIN CORDA

SEI Stockholm Environment Institute

SWEDISH INTERNATIONAL DEVELOPMENT COOPERATION AGENCY

UNDP

SAHARA AND SAHEL OBSERVATORY

MEĐUNARODNA KOMISIJA ZA SLIV RIJEKE SAVE

INTERNATIONAL SAVA RIVER BASIN COMMISSION

List of appended papers

This thesis is based on the following scientific papers:

Paper I

Almulla, Y., Ramos, E., Gardumi, F., Taliotis, C., Lipponen, A., & Howells, M. (2018). *The role of energy-water nexus to motivate transboundary cooperation: An indicative analysis of the Drina River Basin*. http://dx.doi.org/10.5278/ijsepm.2018.18.2

Paper II

Almulla, Y., Fejzic, E., Zaimi, K., Sridharan, V., de Strasser, L., & Gardumi, F. (Under Review). Hydropower and Climate Change, insights from the Integrated Water-Energy modelling of the Drin Basin. *Energy Strategy Reviews*.[under review].

Paper III

Almulla, Y., Ramirez, C., Pegios, K., Korkovelos, A., Strasser, L. de, Lipponen, A., & Howells, M. (2020). A GIS-Based Approach to Inform Agriculture-Water-Energy Nexus Planning in the North Western Sahara Aquifer System (NWSAS). *Sustainability*, *12*(17), 7043. https://doi.org/10.3390/su12177043

Paper IV

Almulla, Y., Ramirez Gomez, C., Joyce, B., Huber-Lee, A., & Fuso Nerini, F. (2022). From participatory process to robust decision-making: An Agriculture-water-energy nexus analysis for the Souss-Massa basin in Morocco. *Energy for Sustainable Development*. 70, 314–338. https://doi.org/10.1016/j.esd.2022.08.009

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List of Abbreviations

AR6	The IPCC sixth Assessment Report
AVE	Area- Volume-Elevation curve
BCM	Billion Cubic Metres
CAPEX	Capital Cost
FAO	UN Food and Agricultural Organisation
GCM	Global Climate Models
GERD	Grand Ethiopian Renaissance Dam
GHG	GreenHouse Gas
GIS	Geographic Information System
Gt	Billion tonnes
GWh	Gigawatt-hour
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOE	The Levelised Cost of Electricity
LEAP	Long-range Energy Alternatives Planning
M.A.S.L	Meters above sea level
MCM	Million Cubic Metres
MENA	Middle East and North Africa
MW	Megawatt
NGOs	Non-Governmental Organisations
NWSAS	North Western Sahara Aquifer System
OnSSET	Open Source Spatial Electrification Tool
OSeMOSYS	Open Source Energy Modelling System
OSS	Sahara and Sahel Observatory
PV	Photovoltaic

RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
RDM	Robust Decision Making
RDS	Robust Decision Support
RES	Reference Energy System
RQ	Research Question
SDGs	Sustainable Development Goals
SEI	Stockholm Environmental Institute
SMHI	The Swedish Meteorological and Hydrological Institute
SSPs	Shared Socioeconomic Pathways
TBAs	Transboundary Aquifers
TBNA	Transboundary Basins Nexus Approach
TJ	Terajoule
TWh	Terawatt-hour
UNECE	United Nations Economic Commission for Europe
UNECE Water Convention	UN Economic Commission for Europe Convention on the Protection and Use of Transboundary Watercourses and International Lakes
VRE	Variable Renewable Energy
WEAP	Water Evaluation and Planning
WEF	Water, Energy and Food
WELMM	Water, Energy, Land, Materials and Manpower.

Glossary

Shared water: in this research, the term 'shared water' refers to surface water and groundwater in both transboundary water basins shared between more than one country and also to local water bodies that are shared between different sectors within a country.

System: "a group of interrelated and interacting elements that form a complex whole."[1]

Sector: refers to the human activity within a system. For instance, the electricity sector is part of the energy system and the agricultural sector is part of the land system.

Transboundary river: a river that crosses the boundaries of more than one country.

Cooperation in water management: refers to any interactions between sectors and/or countries concerning the use and protection of shared rivers, lakes and aquifers.

Nexus: is the set of interactions between selected systems. In the context of this thesis, the nexus refers to the interaction between the water, energy and land resource systems.

Capacity Factor: is the ratio of actual annual output to output at rated capacity for an entire year. It is a measure of a power plant's actual generation compared to the maximum amount it could generate in a given period without any interruption [2], [3].

Pumping energy demand: the amount of energy required to lift water from underground water aquifers to meet irrigation requirements.

1 Introduction

1.1 Background

The relationship between human beings and water resources is inviolable. This relationship assumed this value because of the various uses of water in human life (spiritual, recreational, agricultural, industrial, domestic, hydropower, and many others). Human work has always been required for water capture, treatment and transportation [4]. Throughout history, the presence of major rivers has always been a necessity for civilizations to flourish and economies to develop [5], while effective river management has always been a priority for societies and nations [6]. Today, about 40% of the world's population lives close to the 286 transboundary river and lake basins that supply 60% of the world's freshwater flows and make up about half of the Earth's land area [7]. Moreover, around 2 billion people in the world depend on groundwater sources, which include over 460 transboundary aquifer systems [8] [9].

The socioeconomics of the shared basins extends beyond the water system. For example, agriculture is often a key activity in such areas and is highly dependent on the use of shared water resources for irrigation. In some cases, use for irrigation may well compete with other activities, especially in water-scarce regions. The energy system is another example that interacts with the water system in different ways. Either it relies on the flow of the shared water for its operation, i.e. water for hydropower plants and water for cooling thermal power plants, or energy is needed to make use of the shared water sources, i.e. energy for pumping. Moreover, all these human activities affect the ecosystems of the shared basins. In this dissertation, the term "system" refers to the natural resources (e.g. water, land, energy) or the climate system, while "sector" refers to the human activity within a system, for instance, the agricultural sector is part of the land system or the electricity sector is part of the energy system.

The mismanagement of water resources can lead to catastrophic disasters with an exacerbating domino effect. A clear example is the Aral sea which in the 1950s was the fourth largest landlocked sea on Earth with a total area of 66,000 km^2, just behind the Caspian Sea, Lake Superior and Lake Victoria. To put this into perspective, its area was once roughly equal to that of the Netherlands and Belgium combined [10]. In the 1960s, the Soviet Union launched a project to increase cotton production in the Central Asia region, which required an enormous amount of irrigation that was diverted from the Aral Sea and its tributaries. The Soviet Union managed to boost the area under cotton cultivation from 1.9 million hectares to 3.1 million hectares and production increased from just less than 4.3 million tons in 1960 to 8.7 million tons in 1988, which made the Soviet Union the world's second-largest cotton exporter. In the late 1980s, when the Soviet planners realised that the amount of water reaching the lake was only 10% of the water flow in 1960, it was too late. The Aral's area shrank by 41%, its volume dropped by 67% and the salinity of its water tripled. The large body of water is divided into two, one water mass to the north called the North Aral Sea, and another to the south called the South Aral Sea. The Aral Sea bed became a saline desert [11]. The dissolution of the Soviet Union resulted in the Aral sea becoming a transboundary water body shared between Kazakhstan and Uzbekistan (The drainage basins of the Syr Darya and Amu Darya rivers were additionally shared by Kyrgyzstan, Tajikistan, and Turkmenistan). The crisis in the Aral Sea was inherited by the newly independent states of Central Asia but now disputes and conflicting interests around water diversion and or use are no longer coordinated by Moscow and each state is free to use the shared – and now scarce - resources within its territory as it wishes. This has added new conflicts between upstream states (Kyrgyzstan and Tajikistan) that want to increase hydropower generation and downstream states (Kazakhstan, Uzbekistan, Turkmenistan) that are desperate for water to irrigate their agricultural land [12].

If this story is looked at from the point of view of "system lenses", it is interesting to note that the problem started with the expansion of irrigation (agriculture system) without proper consideration of the water resources. This caused a direct impact on the Aral sea (water system). Consequently, this affected the environment (ecosystem), and the economy (economic system) and caused tension between riparian states (water diplomacy). Additionally, the newly established states (i.e. Kyrgyzstan and Tajikistan) are planning to expand their hydropower generation (energy system) which

threatens the downstream countries" agricultural plans (agriculture system). This clearly illustrates the complex nature of shared water management which extends far beyond the water system.
Another example is the Mekong River Basin in Asia. Thailand as an upstream riparian country is interested in expanding the irrigation of its arid area. It is also in favour of Chinese dam construction (another upstream nation). Laos (a third upstream nation) is also interested in the development of its hydropower resources. All three countries face severe energy shortages and both Thailand and China import hydropower from Laos to mitigate the problem. On the other hand, downstream nations such as Vietnam and Cambodia are concerned about the Chinese hydropower development and blame China for the deterioration of water quality in the Mekong delta (which is very important for Vietnam's agricultural sector) [13].
There are many more examples of poor water management and the resulting catastrophic consequences [14]–[18]. In most cases, the impacts of poor water management extend beyond the water system. On the one hand, this emphasises the interdependencies of the water system with other systems such as energy and food/ agriculture [19] while on the other hand, it highlights the importance of systems thinking and planning in resource management. This is a concept that is not easily translated into policy-making processes in many parts of the world where "silo" thinking and looking at resource systems as isolated individual entities still dominate [20].

Climate change adds another layer of complexity and exacerbates the issue of water management. The latest IPCC sixth Assessment Report (AR6) states that climate extremes are affecting economies and societies and increasing risks across the water, energy and food sectors, especially at transboundary levels. The report also states with a high degree of confidence that the risks in physical water availability and water-related hazards will continue to increase in the mid to long-term future. The report emphasises that challenges in water management will be exacerbated in the near, mid and long term, which will increase the need for climate-informed transboundary management and cooperation [21]. Furthermore, it stresses that coordinated cross-sectoral policies and planning can maximise synergies and avoid the trade-off between mitigation and adaptation [22].

In a response to some of the aforementioned issues (and other sustainability issues), the concept of the Water-Energy-Food nexus was introduced at the Bonn 2011 conference [23]. The background paper to the conference introduces the nexus approach as an approach that integrates management and governance across sectors and scales to support the transition to a green economy and improve resource efficiency and policy coherence [23].

It could be argued that the basis for the water-energy-food nexus goes as far back as 1972 and the publication of “The Limits to Growth”. This work, commissioned by the Club of Rome, used a simulation model to discuss the possibility of exponential economic and population growth with a finite supply of resources. The report called for substantial changes in resource consumption to prevent a sudden and uncontrollable decline in population and industrial capacities [24]. Around the same time, a second study introduced the (WELMM approach) to evaluate the resource requirements for the development of energy resources. The WELMM focused on five limited resources: **W**ater, **E**nergy, **L**and, **M**aterials and **M**anpower. The study highlights that “a major consequence of resource scarcity is that the problems related to resource management cannot be analyzed by considering each resource separately: this would obscure the systems aspects of the problem” [25]. In 2009 another landmark study, introduced the concept of ”Planetary Boundaries” [26]. Rockström et al. introduced nine areas from climate to biodiversity, as being fundamental in maintaining a ‘safe operating space for humanity”.

Despite this early realisation of the interconnectedness of resource systems, research on the WEF nexus only gained momentum during the last decade where both policy and academic research are concerned. Several methods and approaches [27]–[30] were introduced to operationalize the nexus [31], [32]. Among them is the CLEWs framework. This framework addresses the interactions between Climate, Land-use, Energy and Water systems [33], [34] and uses modelling tools to quantify the impacts of the nexus interactions. Another example is the Transboundary Basins Nexus Approach (TBNA) introduced by the United Nations Economic Commission for Europe (UNECE) the purpose of which is to assess the nexus between water-energy-food-ecosystems in transboundary water basins [29], [30].

The United Nations Sustainable Development Goals (SDGs) can be seen as another way to look at development challenges [35]. Not just for addressing issues relating to shared water but also for achieving sustainability at national and global levels. These ambitious goals are highly interconnected meaning that working towards any of the SDGs may negatively or positively impact other SDGs [36], [37]. Knowing that SDG 2 tackles food and agriculture, SDG 6 focuses on water and sanitation, SDG 7 on sustainable energy and SDG 13 on climate change, brings us back to the discussion of the interconnected nature of the resource systems in our world. Furthermore, SDG target 6.5 calls for the implementation of integrated water resources management at all levels by 2030, including through transboundary cooperation as appropriate.

The geographical location is important. Although average global precipitation is about 700 millimetres (mm) per year, it varies among and within continents. Regions that receive low rainfall (less than 500 mm per year), such as the Middle East and North Africa (MENA) region, suffer from water shortages and inadequate crop yields [38]. This particular region is the most water-scarce in the world with more than 60% of its population living in areas of high or very high surface water stress. Climate-related water scarcity is expected to cause economic losses of 6-14 % of GDP by 2050 in the MENA region [39]. Globally, freshwater-related risks are increasing and about four billion people are facing water scarcity [40]. In contrast, areas with high precipitation and redundant water resources such as Europe and the Balkans, usually suffer from periodic floods [41]. Records show that between 1870 and 2016, Europe experienced 1564 flood events with 56% categorised as flash floods (river floods lasting less than 24 h), 39% as river floods, 4% as coastal floods and the remaining 1.5% as compound events caused by the co-occurrence of a storm surge and high river flows [42]. The IPCC AR6 observed an increasing trend in river flooding and projects an increase in flash flooding in Western, Central and Eastern Europe given global warming of 1.5 °C and 2 °C [21], [43].

Water-related disasters account for 90% of all-natural disasters worldwide [44]. Additionally, in the last 50 years, there have been 37 acute transboundary water disputes. Nevertheless, two-thirds of the 286 transboundary rivers do not have any cooperative management framework, not to mention the transboundary aquifer systems [45]. In addition, where such frameworks exist, they are often underfinanced or not well situated to bring stakeholders to a sustainable cooperation level. This makes the need for effective cooperative management of shared water resources very critical [45].

This thesis contributes to the discussion on cooperation concerning shared water. **It aims to support shared water management by using the WEF-nexus approach to quantify the benefits of coordinated management, motivate cooperation, and identify trade-offs in the optimal use of resources**. In this research, the term "shared water" refers to surface water and groundwater in transboundary water basins shared between more than one country and also to local water bodies that are shared between different sectors within a country. The term "nexus" refers to the interactions between the selected systems (energy, water and agriculture).

Two different, yet complementing, geographic locations were selected for this research. One is the Balkans of Southeastern Europe which faces water redundancy and flood issues and the other is the MENA region which suffers from water scarcity. In each region, two representative shared water case applications were chosen. The Drina and the Drin river basins represent the characteristics of Southeastern Europe while the North Western Sahara Aquifer System (NWSAS) and the Souss-Massa Basin represent the characteristics of the MENA region. Three of the case applications are transboundary (Drina, Drin and NWSAS) while the last case application (Souss-Massa Basin) is a subnational basin.

1.2 Literature gaps and research questions

Transboundary water cooperation is defined as "*any action or set of actions by two or more riparian states that lead to the enhanced management or development of the shared water body (e.g. river, lake or aquifer) to their mutual satisfaction* [46]". This definition extends the transboundary waters to include the catchment area of the shared water and not just the water body. In other sources, transboundary cooperation relates solely to the existence of transboundary water agreements [47]. Hence, there is no consensus on one single definition of transboundary water cooperation [48].

The concept of cooperation encompasses a wide spectrum of measures. It can be soft or "ineffective cooperation" such as bilateral discussions and frameworks. Or it can be hard or "effective" cooperation consisting of discrete and concrete actions such as information sharing, environmental assessments, agreements on water allocation and the development of permanent shared management institutions [46] [49]. It is expected that moving from "ineffective" towards "effective" cooperation would generate greater benefits for the cooperating parties [46]. Sadoff and Grey [6] summarised four levels of cooperation benefits: benefits to the river (e.g. better ecosystem), benefits from the river (e.g. increased food and/or energy production), reduction of costs caused by the river (e.g. tensions avoided), and finally benefits beyond the river (e.g. cooperation between the states and/or economic integration) [6]. However, multiple factors affect the level of cooperation such as political will and stability, governance, power relations between the parties, the cost of cooperation, the realisation of gains or benefits, and the availability of data and tools to facilitate cooperation, among others [46] [50].

Political will and stability can be driving forces for cooperation or conflict, as shown by [51] in the case of the Euphrates and Tigris Rivers shared between Turkey, Syria and Iraq. Kibaroglu and Gursory [51] showed that cooperation in this basin passed through three different phases. First was the competitive or tension phase that lasted from 1960 until the turn of the millennium. This phase was characterised by confrontation and tension as the riparian states developed economic plans and policies for the basin independently of each other or at best based on merely unilateral agreements. The second phase started in the first decade of the 2000s and witnessed a shift in the management of water resources to a more cooperative approach - primarily due to the change in governance in one of the riparian states (Turkey). Then the third phase was influenced by the civil war in Syria and instability in Iraq which negatively impacted the bilateral and trilateral relations among the riparian states. The study concluded that the overarching and chronic problem of confrontational political relations in the region has had a negative effect on the development of transboundary water cooperation for decades.

The governance of shared water bodies is also very important. Nations have a long history of shared water governance and management and today there are some 3,600 transboundary agreements in force [49]. However, the existing agreements still lack workable monitoring provisions, enforcement mechanisms, and specific water allocation provisions to make it possible to address questions related to variations in water flow and quality [49] [52]. Furthermore, in many cases, transboundary basins are coordinated by multiple bilateral agreements or in other cases excluding some of the affected riparian states from the agreement (e.g. the 1929 and 1959 agreements concerning the Nile river [50]) rather than having one multilateral agreement involving all riparian states [46].

Where international water law instruments are concerned, three laws are worth noting here [49]. First is the 1997 UN Convention on the Non-Navigational Uses of Transboundary Waters (UN Watercourses Convention – UNWCC) [53]. Second is the 1992 UN Economic Commission for Europe Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE Water Convention) [54], and third is the UN Draft Articles on Transboundary Aquifers (Transboundary Aquifers Articles) [55]. These laws and conventions regulate “the rights and duties of the states, define their legal responsibilities in their conduct with other riparian states, and define clear procedures for resolving conflicts concerning transboundary watercourses [46]”.

An absence of cooperation will only result in conflicts. For a long time, transboundary water research focused on conflicts [56]. Conflicts concerning shared waters can be attributed to three main reasons: a) competition between upstream and downstream states due to changes in water demand, b) activities that result in water pollution and damage the ecosystem, and c) uncoordinated groundwater withdrawals that threaten another riparian state's share of the groundwater source [49]. A typical conflict might arise from an upstream state's hydropower development which is detrimental to downstream dependence on the water resource for irrigation. A clear example is a long-running conflict in the Nile River Basin between Egypt and Sudan and their upstream neighbours - mainly Ethiopia which unilaterally reallocated the river in 2010 to build the Renaissance dam [49] [57], [58] [50].

Where the Nile River is concerned, the energy sector can be seen as a source of tension and conflict between countries. However, the energy sector can play other roles in the shared water context. As Cascão et. al [56] concluded, the relationship between transboundary water management and energy is not well understood [56]. One sign of this can be the misrepresentation of the energy sector in dialogues concerning transboundary basins. There are several reasons for this, such as the misperception that this is a water issue, the common practice of water ministries and agencies controlling the basin commissions instead of there being a multi-sectoral management team, and the profit-driven attitude of the energy utilities which gives lower priority to environmental and cooperation issues.

The role of the energy sector in shared water basins is very important, however, there is little research about it in the literature [56] [59] [60]. Several studies have investigated the role of the energy sector from a governance perspective [51] [50]. Other studies have "qualitatively" explored the benefits of cooperation in water management vis-a-vis the energy sector. For example, Sadoff and Grey [6] looked at energy (mainly hydropower) as an opportunity that can increase the benefits "from the river" through improved water management and hence increased hydropower production. This may lead to additional investments in infrastructure and strengthen trade relations [6]. Quantification and modelling have often been used but focused on basin hydrology and water issues [11], [61]–[64]. A few studies have “quantitatively” addressed the energy aspect in shared water basins. However, these studies were focused on sub-national basins and selected hydropower plants. For example, Yang et.al.[65] used a hydro-agro-economic model with an extended module for agricultural energy use to study the impact of a range of climate change scenarios on the water, energy and food aspects in the Indus Basin in Pakistan [65]. Basheer and Elagib used a water allocation model and river and reservoir simulation software to study the operation of Jebel Aulia Dam (JAD) on the White Nile in Sudan. The study suggested a new operating policy that has the potential to increase water efficiency (energy output per unit of water). The researchers called for a basin-wide assessment that includes all the hydropower storage dams [57].

This was partially addressed in [66] where the cooperation between the Blue Nile riparian states (Sudan and Ethiopia) on the WEF nexus was studied. The long-term economic gains at the basin and country levels were quantified using a daily model for the basin. The hydrological process, irrigation water requirements, and water allocation were simulated and the operation of three dams was studied - the Grand Ethiopian Renaissance Dam (GERD), the Roseires dam and the Sennar dam in Sudan [66]. The impact on the energy sector was explored using a water-centred modelling tool (e.g. RiverWare [67]) and the representation of the electricity system was limited to a few hydropower plants in the basin. Another example of the quantification at the transboundary basin was presented in [68], where a hydrologic model was coupled with a water resources system model (hydro-economic model) to explore the impact of climate change on the Brahmaputra River Basin in South Asia which is shared between China, India, Bhutan and Bangladesh. This study assessed the interaction between water, energy and food in the Brahmaputra Basin and demonstrated alternative basin trajectories under different climate and social conditions. In other words, it evaluated scenarios related to current climate and water uses, the potential impacts of climate change and human development at the national level and the resulting policy implementation [68]. In summary, it is possible to conclude that although these studies were implemented at a transboundary level, they either did not address the issue of cooperation between riparian states (e.g. [68]) or where they did consider cooperation, they often relied on water-centred modelling tools and limited the energy sector to a few hydropower plants in the basin. As a result, country-wide and region-wide interdependencies of the energy and water systems were ignored. Furthermore, the use of open-source modelling tools in such contexts remains limited. This leads to the first research question that this thesis aims to address:

> ***Research question 1****: What role can the energy sector play in motivating shared water cooperation?*

This gap in the research has subsequently been confirmed by other independent parallel research that followed this thesis work such as [69]. In this study, Basheer et. al. demonstrated that a coordinated operating strategy could allow the Grand Ethiopian Renaissance Dam to help meet water demands in Egypt during periods of water scarcity and increase hydropower generation and storage in Ethiopia during high flows. A provided open-source economy-wide model includes water, energy, and land components and runs dynamically for a multiyear period. Similarly, Gonzalez et.al assessed the benefits of cooperation in the management of new dams in water basins that lack formal sharing arrangements. The study compared uncooperative versus cooperative reservoir operations using a multi-criteria comparison and applied the approach to the Pwalugu Multipurpose Dam (PMD) in Ghana in the Volta River Basin [70].

Returning to the discussion on climate change, it is important to highlight the relevance of shared water management in this respect. Currently, some 1,330 GW of installed hydropower accounts for almost 16% of supplied global electricity, followed by 6% from wind and 2.8% from solar photovoltaic (PV) [71]. According to the International Energy Agency (IEA) report ”Net Zero by 2050”, the world needs to double its hydropower capacity by 2050 to maintain the global temperature increase below 1.5 degrees Celsius relative to the pre-industrial era [72]. This means that the current hydropower capacity, which was installed over the last 100 years, needs to be built and installed in just 30 years [73]. What makes the transboundary context and cooperation very important in this context is the fact that more than 70% of the new hydropower projects have transboundary dimensions [59]. Therefore, understanding future climate changes and the resulting impact on hydropower and other renewables is of crucial importance for decision-makers [74], especially in a transboundary set-up.

Climate change and hydropower have been explored in the literature at different scales: global [75], regional [74], [76], national [77], [78] and sub-national [79]–[83]. There is also a growing interest in understanding the impact of climate change on shared water basins [84]–[91]. For instance, Link et. al. [87] examined how physical and socioeconomic variables (e.g. climate change, political and cultural drivers), interact to affect the likelihood and intensity of water conflict and water cooperation in transboundary river basins. Their study was based on a literature review and no quantification was involved. Munia et. al. [86] looked at global transboundary basins to assess how water stress (water use compared to its availability) has developed in the past and how it may change in future scenarios. Here, output data from global hydrological models were used, and scenarios were created using projected climate change scenarios based on Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs). The study concluded that the intensification of stress in future scenarios would occur mostly in Central Asia and the northern part of Africa. However, although a quantification approach was used and selected aspects of climate change in transboundary water basins were explored, the impact on the energy sector was not considered.

With regards to the energy sector, Yun et. al. [88] used a modelling-based approach to study the trade-offs between flood control and hydropower generation in the transboundary Lancing-Mekong River Basin. The study concludes that flood frequency and magnitude can be effectively reduced by regulating water discharges and levels in streams. However, this comes at the expense of reduced hydropower generation. The study highlights the importance of coordinating water and energy management across countries in this transboundary river basin. Nevertheless, it limits the consideration of the energy sector to the hydropower plants in the river basin, for instance, it does not look into other renewable energy sources such as solar and wind.

This reveals a clear gap in the literature in understanding the country-wide or region-wide impacts of climate change in shared water basins. One study worthy of mention in this context is the study conducted by Spalding-Fecher et. al.[85] who developed an integrated water and power model to explore a range of climate change and socioeconomic scenarios for the Zambezi River basin. The study provides insights into the impact of climate change on individual hydropower plants as well as on the entire electricity generation systems of riparian states. Two modelling frameworks were soft-linked: the Long-range Energy Alternatives Planning (LEAP) and the Water Evaluation and Planning (WEAP). This study is directly focussed on the gap in the literature, but it is just a single early study and unfortunately, the modelling frameworks are not open-source, which challenges the replicability of any future study.

Therefore, the literature in this area is still at an early stage and more investigation into a wider spectrum of cases is needed. For instance, Zhong et. al [90] highlight that there is a need for new techniques to integrate wind-photovoltaic-hydropower operation because hydropower is normally used to balance fluctuations in variable renewable energy (VRE) sources (solar and wind). This leads to the second research question in this thesis:

> ***Research question 2:*** *What risks and opportunities emerge from the interplay between climate and renewable energy in shared basins?*

So far, the focus of this discussion has been on surface water. However, groundwater sources are equally important and are associated with different challenges. Groundwater sources make up 97% of non-frozen freshwater, supplying almost 50% of the world's population with drinking water and irrigating over 40% of the world's production of irrigated crops. Like surface water, the flow of groundwater does not stop at national borders. Today, there are 468 identified transboundary aquifers and aquifer systems (see Table 1) compared to 366 in 2015. This number is likely to increase in the future when further studies are conducted. Therefore, the mapping, assessment, governance and management mechanisms for shared aquifers are of great importance [9].

Table 1. Summary of Transboundary Aquifers (TBAs) of the World as of 2021 [9]

#	Region	TBAs
1	Africa	106
2	Americas	135
3	Asia and Oceania	130
4	Europe	97
	World	**468**

Unlike shared river basins, cooperation relating to shared groundwater basins is still at an early stage. Of the 468 transboundary aquifers, only six aquifers have a bilateral or multilateral cooperation mechanism: (1) the Guaraní Aquifer System in Brazil, Argentina, Paraguay, and Uruguay; (2) the Franco-Swiss Genevese Aquifer System in France and Switzerland; (3) the North western Sahara Aquifer System in Algeria, Libya, and Tunisia; (4) the Iullemeden Aquifer System in Mali, Niger, and Nigeria; (5) the Nubian Sandstone Aquifer System shared by East Libya, Egypt, Northeast Chad, and North Sudan, and; (6) the Al-Saq/Al-Disi Aquifer System in Jordan and Saudi Arabia [92]. In addition, about 36 transboundary aquifers located within river basins have treaties that specifically regulate groundwater issues [93]. There are several reasons for the low number of groundwater agreements such as the “invisible” nature of groundwater [93], lack of data, disharmonised data, and the lack of institutional capacity for groundwater management and governance [92].

Despite the large number of studies on groundwater, there are (at the time of writing) only a handful of studies that address shared aquifers beyond the water system. Many of the studies on groundwater aquifers focus solely on water aspects and often omit consideration of the link with other systems such as energy [94]–[98]. Other studies focus on national [99], [100] or subnational groundwater sources [94], [96] and do not consider transboundary aquifer systems. In the very few transboundary studies such as [101], [92], the focus is on governance aspects and comparing different groundwater agreements to motivate and guide transboundary groundwater collaboration. The studies highlight the importance of data sharing and stakeholder engagement in enhancing aquifer management.

Thus, important gaps exist in the literature. No research has quantitatively and simultaneously studied the impact of agriculture, water and energy systems in a transboundary aquifer context using open-source tools. Insights into these aspects are critical for the robust, coherent and sustainable management of shared groundwater sources. This leads to the third research question:

> ***Research question 3****: What benefits can the consideration of the energy-water-agriculture nexus bring to shared groundwater management in water-scarce areas?*

The growing dependency on groundwater sources can be attributed to many reasons, the availability of electrical power, the variety of options for powering pumps, the technological advancement of deep-well pumping [93] and the growing need to irrigate crops. Today, irrigated agriculture expands over 280 million hectares of irrigated cropland and provides more than 40% of global food production [98]. Over one-third of the world's production of irrigated crops relies on groundwater sources [9] from which water is often extracted using pumps powered using fossil-fuels. According to UN Food and Agricultural Organization (FAO) statistics (FAOSTAT), in 2019 global agri-food system emissions were 16.5 billion metric tonnes (Gt CO_2 eq. yr^{-1}), corresponding to 31 % of total anthropogenic emissions. Of these, global emissions within the farm gate (an indicator showing emissions from crop and livestock production processes including on-farm energy use) were 7.2 Gt CO_2 eq. yr^{-1} [102], [103]. In the same year, global energy use in the agricultural sector was estimated at 9.2 million Terajoule (million TJ) or about 2,550 TWh, of which 43% came from Gas-Diesel oil and 28% came from electricity as shown in Figure 1 [103]. Groundwater pumps are the largest consumers of energy in irrigated agriculture, especially in water-scarce regions [104]. This highlights the importance of agricultural sector decarbonisation especially in shared water basins and in water scare regions.

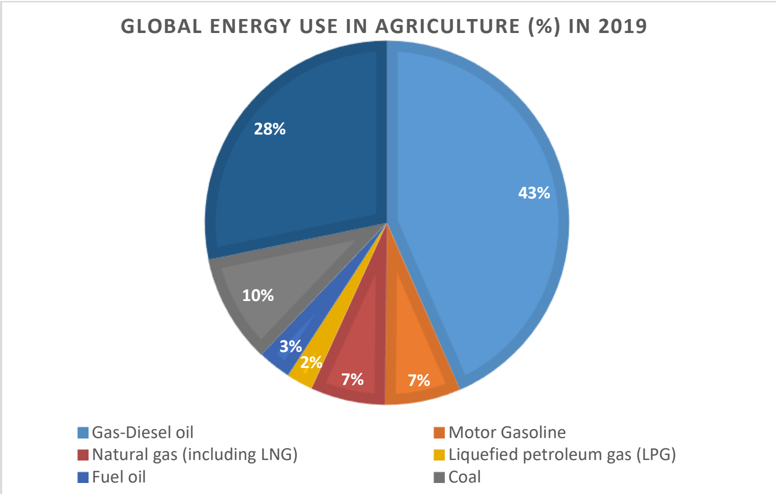

Figure 1. Share of global energy use per fuel type in agriculture in 2019.
Self-compilation based on FAOSTAT data [103].

This is not a sectoral challenge, but rather a multi-sectoral challenge that calls for close collaboration between the agriculture, water and energy sectors. Therefore, the nexus approach is crucial in tackling this question. The nexus literature is extremely extensive in respect of agricultural productivity, crop production, irrigation and solar pumping topics [105], [94], [106]–[110], [98], [111]–[116]. However, consideration of the decarbonisation of the agricultural sector is limited. For example, Aggarwal et al. described a range of practices for reducing greenhouse gas (GHG) emissions in the agricultural and forestry sectors in the US [117]. However, the list of practices does not include groundwater pumping. Aghajanzadeh and Therkelsen introduced a framework for decarbonising the electricity grid by connecting on-farm electricity to the national grid and improving grid flexibility through agricultural demand response strategies. The authors argue that connecting various on-farm electricity-consuming equipment (such as groundwater pumps, surface water pumps, etc.) to the appropriate grid need(s) can enhance flexibility and allow the integration of more intermittent renewables [104]. However, their study does not explore the impact of a technology shift from fossil-based to low-carbon technologies. This highlights

the importance of rural electrification and irrigation electrification which was qualitatively analysed by [118].
Thus, it can be concluded that important gaps exist in the literature. There is a need for improved understanding of the role of the agricultural sector in the transition to a low-carbon economy. There is also a need to understand how the nexus approach would support such a transition, especially in a shared water context. This leads to the fourth research question in this thesis:

> ***Research question 4****: How can the consideration of the energy-water-agriculture nexus accelerate the low-carbon transition in the agricultural sector?*

In summary, the **objective of this thesis is to support the coordinated management of shared water resources. The WEF-nexus approach is used to motivate cooperation, quantify the benefits of coordinated management and identify trade-offs in the optimal use of resources**.

Four research questions have been identified to achieve this aim, and for clarity, these are listed together here:

- *What role can the energy sector play in motivating shared water cooperation?*
- *What risks and opportunities emerge from the interplay between climate change and renewable energy in shared basins?*
- *What benefits can the consideration of the energy-water-agriculture nexus bring to shared groundwater management in water-scarce areas?*
- *How can the consideration of the energy-water-agriculture nexus accelerate the low-carbon transition in the agricultural sector?*

1.3 Thesis organization

This dissertation encompasses two parts. The first is the thesis and the second is a compilation of scientific publications (papers). The thesis is structured into four main chapters. The first chapter starts by introducing the research topic, the rationale and the scope. It then summarises key gaps in the literature, leading to the research questions. The chapter concludes with an overview of the case applications and highlights the geographic scope of the research. The second chapter presents the methods used to address the research questions. The third chapter covers the results and discussions. Finally, the fourth chapter contains the concluding remarks, showing how each question was addressed and gives some indications of the limitations of this work before providing recommendations for future research on the topic.

1.3.1 Appended publications

The following scientific publications form the basis of this dissertation. Three of them have been published, while one is under review at the time of writing.

Paper I

Almulla, Y., Ramos, E., Gardumi, F., Taliotis, C., Lipponen, A., & Howells, M. (2018). *The role of energy-water nexus to motivate transboundary cooperation: An indicative analysis of the Drina River Basin*. http://dx.doi.org/10.5278/ijsepm.2018.18.2 [119].

Author's contribution:

The author led the authorship of this paper. This included development of the model and scenarios, data collection, running the model, plotting and analysing the results, extracting insights, and responsibility for writing the major part of the paper. Other co-authors assisted in the conceptualisation, provided initial data, supported model debugging and results refinement, and contributed to writing and revising the paper.

Paper II

Almulla, Y., Fejzic, E., Zaimi, K., Sridharan, V., de Strasser, L., & Gardumi, F. (Under Review). *Hydropower and Climate Change, insights from the Integrated Water-Energy modelling of the Drin Basin*. Energy Strategy Reviews.[under review].

Author's contribution:

The author led the development of the model and enhancement of the storage representation in the model compared to paper I. The author was responsible for scenario development, running the model, developing scripts to extract results and compare scenarios, drawing conclusions, and leading the writing of the article. The other authors contributed to the hydrological modelling and data collection and provided supervision and guidance throughout the analysis and publishing process.

Paper III

Almulla, Y., Ramirez, C., Pegios, K., Korkovelos, A., Strasser, L. de, Lipponen, A., & Howells, M. (2020). *A GIS-Based Approach to Inform Agriculture-Water-Energy Nexus Planning in the North Western Sahara Aquifer System (NWSAS)*. Sustainability, 12(17), 7043. https://doi.org/10.3390/su12177043 [120].

Author's contribution:

The author led the analysis and authorship of this paper. The author carried out the collection and processing of GIS datasets, led the dialogues with stakeholders to define the scenarios, developed the model and refined the scenarios, extracted results, and insights and was largely responsible for writing the paper. The rest of the authoring team contributed to the analysis by providing the initial code for the evapotranspiration calculation [121], and assisting with GIS and Python-based modelling - especially for the cropland calibration module. They also provided supervision and guidance throughout the analysis.

Paper IV

Almulla, Y., Ramirez Gomez, C., Joyce, B., Huber-Lee, A., & Fuso Nerini, F. (2022). *From participatory process to robust decision-making: An Agriculture-water-energy nexus analysis for the Souss-Massa basin in Morocco*. Energy for Sustainable Development. 70, 314–338. https://doi.org/10.1016/j.esd.2022.08.009 [122].

Author's contribution:

The author led the authorship of this paper and the energy modelling part of the analysis. This included conceptualisation, contributing to the geospatial data collection and processing, developing the energy model structure, especially the decarbonisation strategies, extracting insights and drawing conclusions. The author led the writing of the article and the review process. Other co-authors contributed to the water modelling using WEAP and soft linking of water and energy models, assisted with the data gathering and writing of the paper and provided valuable supervision and guidance throughout the analysis.

Each of the research questions presented in section 1.1 is addressed by one or two of the journal articles as shown in Table 2. Research question I, on the role of the energy sector in motivating cooperation in respect of transboundary water, is addressed in paper I and paper II. Research question II, on the implications of climate change on the security of electricity supply in shared water basins and the role of variable renewable energy, is addressed by paper II. Research question III, on the benefits of integrated energy-water-agriculture modelling in managing shared groundwater management, and research question IV, on integrated energy-water-agriculture nexus modelling and the shift to low-carbon agriculture, are addressed in papers III and IV. Each paper considers different systems (or resources). The energy and water systems are the main thread and as such are considered in all papers. The climate system is considered in paper II from the adaptation perspective and in paper IV from the mitigation perspective. The agricultural aspects are considered in papers III and IV. This sector is represented by estimating the irrigation demand of different crops and exploring different decarbonisation strategies. Other activities in the food production chain (e.g. post-harvesting activities, machinery use, storage and transportation) are beyond the scope of this analysis.

Table 2. Mapping of the appended papers to research questions and the key characteristics of each study

	Papers			
	I	**II**	**III**	**IV**
Research questions	RQ1	RQ1 & RQ2	RQ3 & RQ4	RQ3 & RQ4
Geographic scope	Balkans (Drina Basin)	Balkans (Drin Basin).	North Africa (NWSAS basin).	North Africa (Souss-Massa)
Scale	Transboundary basin (3 countries)	Transboundary basin (3 countries)	Transboundary basin (3 countries)	Sub-national (1 country)
Water source	Surface water	Surface water	Groundwater	Surface water and groundwater
Systems considered	Water and Energy	Water, energy and climate (adaptation)	Agriculture, water and energy	Agriculture, water, energy and climate (mitigation)
Key challenges	Water redundancy (floods)	Water redundancy (floods)	Water scarcity (droughts)	Water scarcity (droughts)

1.3.2 Additional publications and reports

In addition to the aforementioned papers, the author contributed to several publications and reports that informed this dissertation as listed below:

1. Ramirez, C., **Almulla, Y.**, & Fuso-Nerini, F. (2021). *Reusing wastewater for agricultural irrigation: A water-energy-food Nexus assessment in the North Western Sahara Aquifer*

System. Environmental Research Letters. https://doi.org/10.1088/1748-9326/abe780 [112].

2. Ramirez, C., **Almulla, Y.**, Joyce, B., Huber-Lee, A., & Nerini, F. F. (2022). *An assessment of strategies for sustainability priority challenges in Jordan using a water–energy–food Nexus approach*. Discover Sustainability, 3(1), 23. https://doi.org/10.1007/s43621-022-00091-w [123].

3. Gardumi, F., Shivakumar, A., Morrison, R., Taliotis, C., Broad, O., Beltramo, A., Sridharan, V., Howells, M., Hörsch, J., Niet, T., **Almulla, Y.**, Ramos, E., Burandt, T., Balderrama, G. P., Pinto de Moura, G. N., Zepeda, E., & Alfstad, T. (2018a). *From the development of an open-source energy modelling tool to its application and the creation of communities of practice: The example of OSeMOSYS.* Energy Strategy Reviews, 20, 209–228. https://doi.org/10.1016/j.esr.2018.03.005 [124].

4. Sridharan, V., Howells, M., Ramos, E., Sundin, C., **Almulla, Y.**, Fuso Nerini, F. (2018b). *The climate-land-energy and water Nexus: Implications for agricultural research*. Presented at the Science Forum 2018, CGIAR Independent Science & Partnership Council, Stellenbosch, South Africa, p. 53. [125]

5. Ramos, E., Taliotis, C., Howells, M., Fuso Nerini, F., Gardumi, F., **Almulla, Y**., Sridharan, V., Moksnes, N., Engström, R.E., Brower, F., Laspidou, C.S., Fournier, M. (2019). Deliverable 1.8 - *Progress of Innovations to Improve the Nexus for the case studies* (H2020 689150 SIM4NEXUS Project Deliverable No. D1.8).[126]

6. UNECE, United Nations Economic Commission for Europe (2017). *Assessment of the water-food-energy-ecosystem Nexus and benefits of transboundary cooperation in the Drina River Basin*. UNECE, Geneva, Switzerland. [16]

7. UNECE, United Nations Economic Commission for Europe (2017). *Policy Brief : Assessment of the water-food-energy ecosystems nexus and the benefits of transboundary cooperation in the Drina River Basin*. UNECE, Geneva, Switzerland. [127]

8. UNECE, United Nations Economic Commission for Europe., (2018). *Methodology for assessing the water-food-energy-ecosystems nexus in transboundary basins and experiences from its application: Synthesis*. New York and Geneva.[30]

9. UNECE, United Nations Economic Commission for Europe, (2020). *The benefits of transboundary water cooperation in the North Western Sahara Aquifer System basin - Policy Brief.* New York and Geneva. [128]

10. UNECE, United Nations Economic Commission for Europe, (2020). *Reconciling resource uses: Assessment of the water-food-energy-ecosystems nexus in the North Western Sahara Aquifer System Part A - "Nexus Challenges and Solutions."* New York and Geneva.[129]

11. UNECE, United Nations Economic Commission for Europe., (2021). *Solutions and investments in the water-food-energy-ecosystems nexus A synthesis of experiences in transboundary basins*. Geneva, Switzerland.[130]

12. GWP-Med, Global Water Partnership – Mediterranean. (2022). *"Phase II - Nexus Assessment for the Drina River Basin"*. Greece. [131]

13. GWP-Med, Global Water Partnership – Mediterranean. (2022). *"Phase II - Nexus Assessment for the Drin River Basin"*. Greece. [132]

14. FAO, Food and Agriculture Organization of the United Nations. (Forthcoming). *"Water sustainability in the NENA region-Nexus Assessment of the Souss-Massa Basin in Morocco"*. Rome.

1.4 Case applications and the geographical scope

The Water Convention, which was adopted in 1992 and entered into force in 1996, is a legally binding instrument promoting the sustainable management of shared water resources. The convention aims to prevent, control and reduce transboundary impact and operationalize the achievement of the 2030 Agenda for Sustainable Development [133]. Serving as a secretary for the water convention, the UNECE carried out several water-food-energy-ecosystems nexus assessments in transboundary water basins. Included among these are the Drina, the Drin and the NWSAS basins [134].

The nexus concept has also been endorsed by other international organizations such as the UN FAO. One of the FAO‘s aims is to support the implementation of the 2030 Agenda for water efficiency and productivity and define the safe boundaries for effective water sustainability in the NENA region [135]. This dissertation contributes to the aforementioned efforts set out in the Water Convention and the 2030 agenda.

The research questions of this thesis are explored in two regions. Each region has its own unique characteristics and water-related challenges. The first region is the Balkans where water resources are redundant. The second region is North Africa, which suffers from water scarcity. In the first region, two transboundary river basins are studied: the Drina river basin and the Drin river basin. In the second region, the first application is on a transboundary groundwater aquifer (the North Western Sahara Aquifer system, NWSAS) and the second is the Souss-Massa Basin, which is a sub-national river basin in Morocco. Table 2 gives an overview of the different characteristics of each case application and the following sub-sections introduce each case application in more detail.

1.4.1 The Balkans - the Drina River Basin

The Drina River Basin extends over an area of 20,320 km^2 [136]. It is formed by two main tributaries (Piva and Tara rivers), both flowing from Montenegro and converging at the border with Bosnia and Herzegovina (Figure 2).

The Drina river feeds into the Sava river which is the main tributary of the Danube river [62]. The Drina Basin is shared between Montenegro (32% of the area of the basin), Bosnia and Herzegovina (36%), Serbia (31%) and a very small part of the north of Albania (less than 1% of the river basin area) [16]. The latter is not considered in this analysis because of its low share.

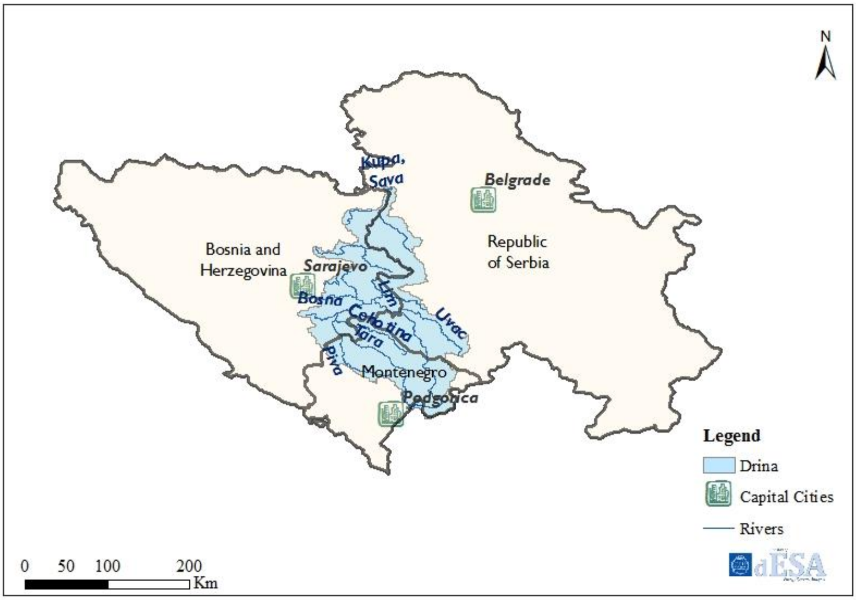

Figure 2. Map of the Drina River Basin (DRB).
(Source: The second transboundary workshop in Belgrade 2016 [137]).

Hydropower plays an important role in the security of electricity supply in the Drina Basin countries. The total installed hydropower capacity in the Drina Basin is 1,722 MW of which Serbia accounts for 1,028 MW, Montenegro for 360 MW and Bosnia and Herzegovina for 334 MW. Along the Drina river, eight reservoirs and hydropower plants exist with a total capacity of 1,088 MW. Five reservoirs are upstream and three are downstream (with respect to the Drina river, the tributaries are upstream and the Drina River is downstream). The largest upstream reservoir is Piva (in Montenegro) with an 880 MCM storage capacity. The other four upstream reservoirs have relatively smaller storage capacities as shown in Table 3. The three riparian states have plans to develop the as-yet under-utilised hydropower potential. However, this is hampered by funding and other constraints. After hydropower, coal-fired power plants are the second most important source of electricity supply in the basin. Bosnia and Herzegovina has 325 MW of coal capacity, Montenegro has 225 MW and Serbia has just 54 MW. The contribution of other renewables such as solar and wind is negligible [16].

Table 3. List of reservoirs and hydropower plants in the Drina river basin

Name	River	Reservoir size (MCM)	Installed Capacity (MW)	Country*	Location with respect to Drina River
HPP Uvac	Uvac	213	36	RS	Upstream
HPP Kokin Brod	Uvac	250	22	RS	Upstream
HPP Bistrica	Uvac	7.6	102	RS	Upstream
HPP Potpec	Lim	27.5	51	RS	Upstream
HPP Piva	Piva	880	360	ME	Upstream
HPP Visegrad	Drina	161	315	BA	Downstream
HPP Bajina Bašta	Drina	218	106	RS	Downstream
HPP Zvornik	Drina	89	96	RS	Downstream
* **BA**: Bosnia and Herzegovina, **ME**: Montenegro and **RS**: Republic of Serbia					

As can be seen from the table above, the hydropower plants along the Drina river serve three different electricity grids yet they rely on the same water flow. The level of cooperation between the countries and utilities on flow regulation is low and informal (or not institutionalised) [138]. This was not the case in the recent past when the countries were part of the former Socialist Federal Republic of Yugoslavia. During this period, the operation of the hydropower plants and the flow regime were controlled so that natural extremes were attenuated by controlling lower and higher flows [139]. The uncoordinated operation of the hydropower plants and their associated reservoir capacity aggravates high water levels and imposes a fluctuating flow regime on the river. This fluctuation affects water availability and electricity generation in downstream plants, which became more vulnerable to both lower and higher flows [140].

Furthermore, the Drina riparian states are contracting parties of the "Energy Community" and one of the priority clusters of the energy community treaty is the creation of a regional electricity market among Western Balkan countries [141]. Additionally, it is planned to integrate the regional electricity market in the Balkans into the Pan-European electricity Market [142]. Cheap hydropower plays an important role in the electricity trade given its high share of the electricity generation mix in the region. Therefore, coordination in hydropower operation has the potential to unlock electricity trade opportunities.

Given the above, the Drina river basin is relevant for addressing RQ1 of this dissertation. The level of cooperation between the riparian states is sub-optimal, nevertheless, there is an ongoing dialogue and interest in improving the cooperation. Such transboundary conditions form an excellent setup to quantify and explore the benefits of cooperation and an opportunity exists for this study to impact decision-making in the region because this study is developed under the framework of the water convention and UNECE.

1.4.2 The Balkans - the Drin River Basin

In the same region of Southeastern Europe, the second case application is the Drin River Basin shared between Albania, North Macedonia, Greece, Montenegro and Kosovo[1]. The Drin river extends over 285 km [64] and creates a basin of 14,173 km^2 [144]. Lakes Ohrid and Prespa in North Macedonia are the origins of the first stream which is known as the Black Drin. The second stream is the White Drin which originates from Kosovo and converges with

[1] UN administered territory under UN Security Council resolution 1244 [143]

the Black Drin to form the Drin River that then flows into Albania and discharges into the Adriatic Sea as shown in Figure 3.

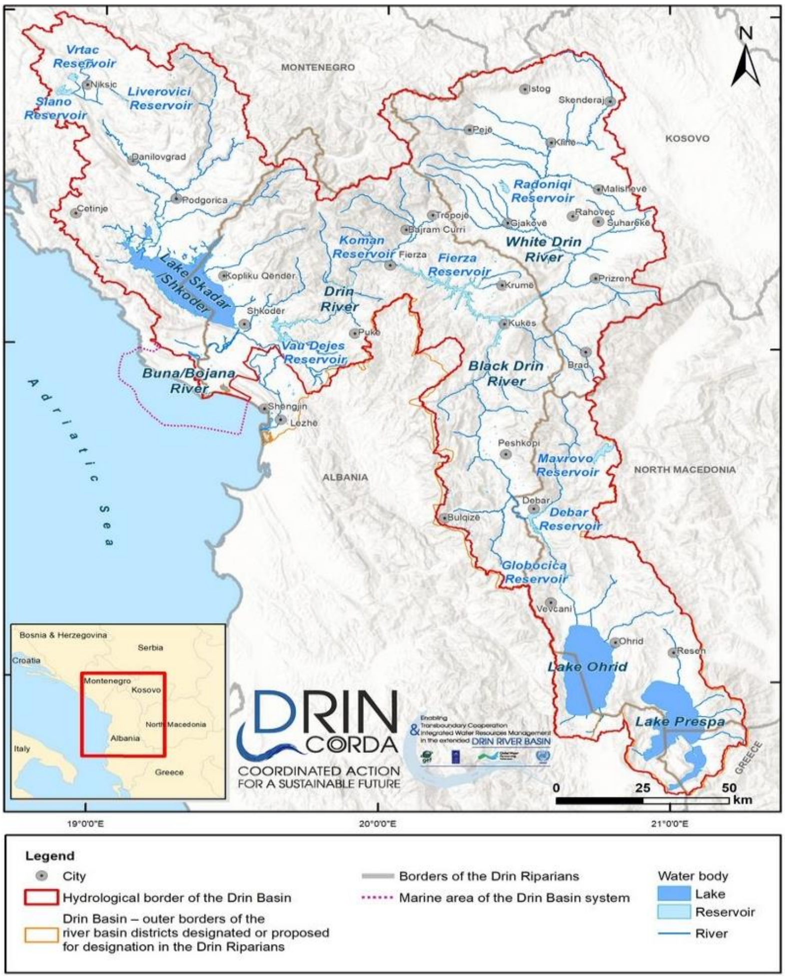

Figure 3. Map of the Drin River Basin and the location of the main hydropower plants.
(Source: Drin Basin - Transboundary Diagnostic Analysis (TDA) [145]).

The Drin Basin hosts 2,015 MW of hydropower, which makes up 31% of the total installed capacity (hydro and thermal) in the associated riparian states. This underlines the importance of the basin for the energy sector in the region. Additionally, Albania, as one of the riparian states, obtains over 90% of its electricity from hydropower. Albania has 1,457 MW (about 60%) of its hydropower capacity installed in the Drin Basin (Figure 4). Montenegro comes second with 307 MW and North Macedonia has 251 MW. The riparian states have plans to diversify their electricity generation mix in the coming years and reduce their dependency on hydropower [146]–[149]. However, the potential of the variable renewable energy sources (solar and wind) has yet to be significantly exploited in the Drin countries as can be seen in Figure 4.

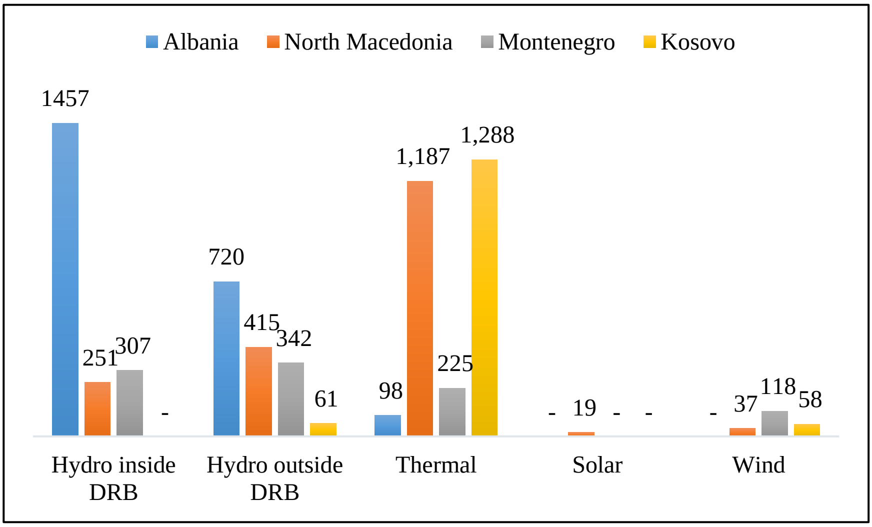

Figure 4. Total installed capacity in the Drin Basin countries by technology.

Like many other transboundary river basins, the Drin Basin has suffered from unsustainable management approaches and conflicting priorities between upstream and downstream countries for several years [143]. The current cooperation at the transboundary level is restricted to emergencies in Albania and North Macedonia [145]. At the national level, the hydropower operators do not feed information into the national flood forecasting system. This means that flood forecasting and dam operation in the basin are uncoordinated and may be sub-optimal [145].

Changes in climate and flow regulation practices have contributed to an increase in the risk of frequent and intense floods [132], [150]. Since 2010, floods have become a significant disaster risk driver[145]. The most severe events recorded in recent years were the inundations of the Shkodra district in Albania in January and December 2010, and the flash floods in the coastal areas of Ohrid in January-February 2015. Historical data show that from 1979 to 1997 there were five major flooding events in Montenegro, but in the six years from 2004 to 2010, floods occurred six times. The total countrywide damage and losses (in Montenegro alone) resulting from the December 2010 floods exceeded EUR 40 million (1.3 percent of GDP) [145].

The flow regime in the Drin River is altered by the operation of two cascades of hydropower plants each on one stream of the river and each serving the national electricity demand in one country [144]. The first cascade is in North Macedonia and consists of two dams and hydropower plants on the Black Drin, namely Globocica and Spilje. The second cascade is in Albania and consists of three large dams and hydropower plants on the Drin River namely: Fierza, Koman, and Vau i Dejës. Additionally, a new hydropower project (Skavica) is under development on the Albanian part of the river and is expected to be operational in the near future [150]. The following table summarises the key characteristics of the dams and hydropower plants in the basin [148], [151].

Table 4. Characteristics of the large dams and hydropower plants along the Drin River.

#	Plant	Storage Volume (MCM)	Power Capacity (MW)	Started Year	Net Head (m)	Water Inflow to turbines (m3/sec)	Avg. output (GWh)*	Spillway capacity (m3/sec)
1	**Globocica**	55.3	42	1965	95.29	2 X 25	186	1,100
2	**Spilje**	506	84	1969	91.3	3 X 36	288	2,200
3	**Skavica****	2300	196	2025	about 140	2 X 87	NA	2,800
4	**Fierza**	2350	500	1976	118	4 X 124	1,363	2,670
5	**Koman**	188	600	1985	96	4 X 150	1,800	3,400
6	**Vau i Dejës**	310	250	1970	52	5 X 113	929	6,700
Total Drin River Basin		5,709	1,672				4,570	18,870

**Mean annual electricity generation (GWh) [148].*

***Skavica hydropower plant is likely to start operation in 2025* [152].

The power utilities in the basin operate the dams with the objective of maximizing electricity production. This means that the water levels are kept at a maximum design level to store as much energy as possible for daily hydropower generation [153]. This approach has been criticised by other stakeholders who have highlighted that altering the operation of the dams to improve flood control would significantly reduce the costs of floods. On the other hand, the operators are concerned that such a practice might jeopardise the security of electricity supply. These aspects make the Drin Basin an interesting case for the investigation of RQ1 and RQ2 of this dissertation. Furthermore, this analysis will contribute to the Strategic Action Program signed by the riparian states in 2020 within the framework of the Memorandum of Understanding for the sustainable management of the Drin Basin that was signed in 2011 [145].

1.4.3 The North Africa region – NWSAS

Moving from surface water to groundwater and from a wet climate to an arid climate, the next case application is the North Western Sahara Aquifer System (NWSAS) in North Africa. With an area extending over 1 million km^2, the NWSAS is the biggest transboundary groundwater reserve in North Africa [129]. Algeria, Libya and Tunisia share this massive water source in different proportions as shown in Table 5 [154]. The three countries rely on this aquifer as the main source of water for all their socioeconomic activities including agriculture, industry and domestic uses. This has resulted in a substantial increase in water abstraction over the last few decades. From about 0.6 billion cubic metres (BCM) in 1970 [155] to over 3.2 BCM in 2018 [156]. On the other hand, the average annual recharge rate is only about 1 BCM per year [157], which is clearly much lower than the abstraction rate. Consequently, this overexploitation has caused a number of challenges, including the depletion of natural springs, water table drawdown, seawater intrusion and deterioration of water quality levels in different parts of the aquifer system, to list just a few [155].

Table 5. Extent of the NWSAS [154]

Parameter	Algeria	Tunisia	Libya
Country area (km^2)	2,381,741	163,610	1,759,540
Country area in the basin (km^2)	700,000	80,000	250,000
Share of national territory in the NWSAS (%)	29	49	14
Share of NWSAS (%) per country	68	8	24

The significant increase in water abstraction is mainly attributed to the expansion of agricultural land (especially irrigated agriculture), the proliferation of wells and the use of inefficient irrigation techniques [155]. The irrigated area has been growing constantly and had reached about 470,000 ha by 2014 [154] of which 270,000 ha is irrigated by NWSAS water[2]. The use of inefficient irrigation systems exacerbates the problem and causes the loss of almost half of the abstracted water. Currently, only 2% (or less) of the irrigated land uses drip irrigation. Over 70% relies on surface irrigation and about 26% uses sprinkler irrigation [18].

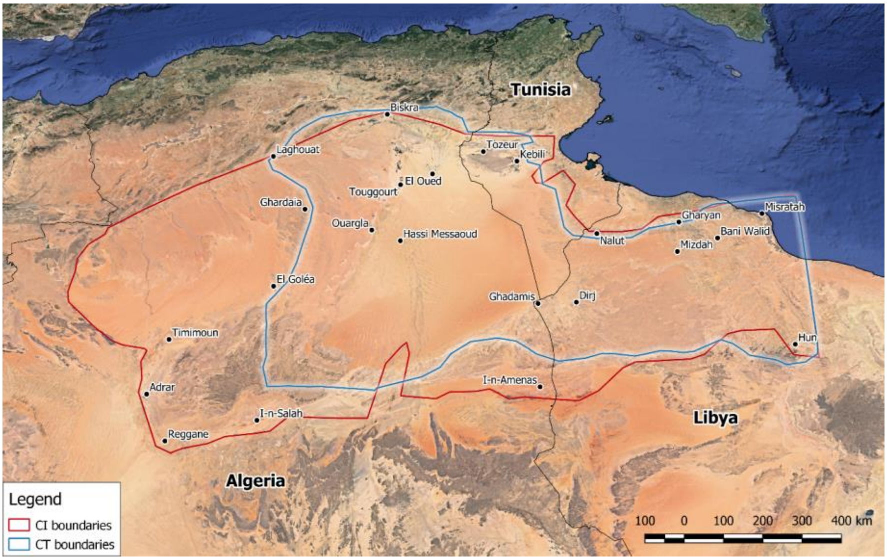

Figure 5. The boundaries of the NWSAS.
(Elaboration by the author.)

The pumping of groundwater is driven mainly by diesel generators while in some locations farmers use electric pumps (e.g the Libyan provinces) [156]. One of the reasons for the high level of use of diesel in groundwater pumping is the cheap subsidised costs of fossil fuels in the three countries. This also applies to the national grids in the riparian states which are heavily dependent on fossil fuels [158]–[160]. Energy subsidies represent a considerable burden on the governments' budgets. For example, in 2018 Algeria spent USD 17,080 million on subsidies for energy products while Libya spent USD 4,698 million in the same year [161]. In Tunisia,

[2] Consultation with experts from Saher and Sahara Observatory (OSS).

energy subsidies reached their highest-ever peak at USD 1,318 million in 2013 which forced the government to reduce energy subsidies and cut this value by almost half within three years [162].

The three countries have ambitious decarbonisation plans to increase the share of renewables. However, implementation remains challenging and progress remains slow. For example, the Algerian Renewable Energy and Energy Efficiency Development Plan 2015–2030 aims to install 4.5 GW of new renewable energy capacity by 2020[3] and a total of 22 GW by 2030. The Tunisian Solar Plan aims to increase the share of renewable energy in the electricity sector to 30% by 2030, with wind power contributing 15% of the total electricity generation, solar PV 10% and concentrated solar power 5% [164].

Since the seventies, Algeria, Libya, and Tunisia have established cooperation in respect of information exchange and consultation to improve the management of the NWSAS. In 2006, the NWSAS "Consultation Mechanism" was established and was given the mandate to: a) produce indicators on water resources and demand, b) elaborate water resource management scenarios for development in the basin, c) reinforce and update the common database through the exchange of data and information, and d) develop and manage common observation networks for the aquifer system. The structure of the Consultation Mechanism is dominated by the water sector and it has a water-driven perspective [129].

Under the framework of the Coordination Mechanism, several studies [165], [166], [154], [17], [155], [18] were conducted on the NWSAS region. In many cases, the studies were coordinated and led by the Sahara and Sahel Observatory (OSS). However, all studies are water-centred and fail to adequately consider other resource systems such as energy.

[3] The total renewable power installed capacity in Algeria reached 686 MW in 2020 [163] which represents 15% of the 2020 target.

The large area, the transboundary dimension, the cross-sectoral nature of the challenges and the established coordination mechanisms are a few aspects that make the NWSAS an interesting case application for exploring RQ3 and RQ4 of this dissertation. Additionally, the work undertaken in this dissertation has informed the ongoing coordination between countries and has, for the first time, applied the UNECE-TBNA to a groundwater basin.

1.4.4 The North Africa region – Souss-Massa Basin

In the previous case applications, the focus was on transboundary water bodies, but there are interesting lessons to be learned concerning shared water bodies that are within the boundaries of one country. Such water bodies are shared between more than one sector, which makes local-level coordination very important. The Souss-Massa Basin in Morocco is a subnational basin that meets the criteria for such a case.

The Souss and Massa rivers forming the Souss-Massa Basin also give it its name. The basin is located in the middle of the western part of Morocco (in North Africa) and covers a total area of 27,000 km^2. Agriculture is the main socioeconomic activity for the 2.56 million people living in this region. Almost 50% of the workforce in the basin works in the agricultural sector [167]. About 175,500 ha of the basin is dedicated to producing crops such as citrus, almond, vegetables and cereals [168]. The Souss-Massa Basin plays an important role in the Moroccan economy. It produces 85% of the vegetables and more than half of the exported citrus fruits. Agriculture, tourism and fishing generate almost 7% of the total Moroccan GDP [169] [170].

Water resources are central to almost every socioeconomic activity in Souss-Massa. On the demand side, irrigation is the highest water consumer using about 94% of total water demand with the remainder being used by industry, tourism and municipal applications [171]. On the supply side, the basin relies on both surface water and groundwater sources. Surface water supplies about 30% of the demand and comes mainly from the reservoirs. Eight large and 16 small dams exist in the basin with a combined capacity of about 800 MCM. The reservoirs are used to control and store water from the Souss and Massa rivers and their tributaries as shown in Figure 6. This water is used for irrigation, drinking and industrial purposes [170]. No hydroelectric plants currently exist in the basin.

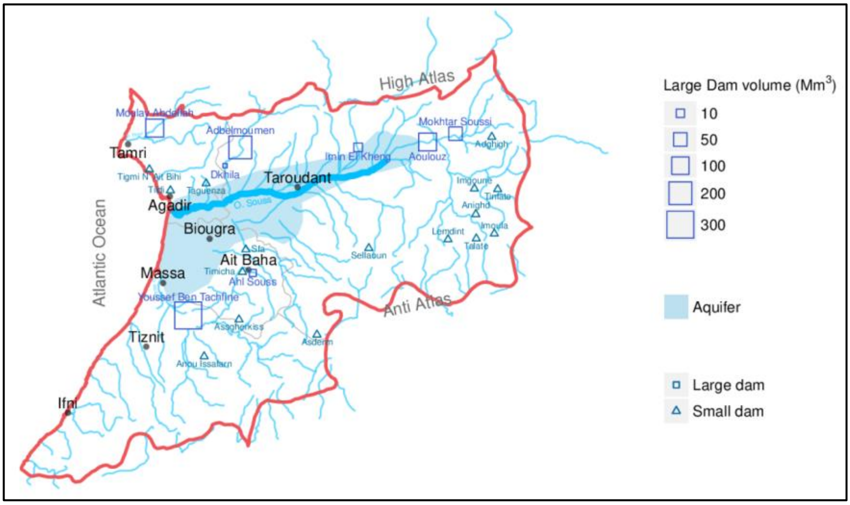

Figure 6. Water resources of the Souss-Massa River Basin.

The second source of water supply in the basin is groundwater aquifers which supply 650 MCM or about 70% of demand [172]. The overexploitation of the groundwater sources over years coupled with the low rainfall (around 250 mm per year in the plain area) has resulted in lowering of the water table levels [173]. For example, the main aquifer in the basin, the Souss aquifer, has witnessed a drop in the water table from 15 m to 30 m, or 0.5-2.5 m per year over the last four decades [174]. The decline in the water table has caused several issues such as seawater intrusion, increased pumping costs, and compromise of water supply security [175].

The number of wells and boreholes in the Souss-Massa Basin has been increasing continuously reaching over 25,000 active boreholes at an average depth of 300 m [172]. This has caused a significant increase in groundwater pumping demand. Records show that since the 1940s, when groundwater pumping started, up until now, pumping demand has increased over 500 times [174]. A mix of energy sources is used to power the pumping activity. Recent estimates show that 70% of the pumps are powered by mains electricity, 20% are driven by butane gas and only 10% use solar PV. Although butane is only used in 20% of the irrigated area, its high subsidy level imposes a heavy strain on the Moroccan government's annual budget. Based on figures from the Directorate of Energy and Mines in the Souss-Massa region, the total consumption of butane for groundwater pumping reached 84,000 tonnes in 2019 [176]. Electric pumps are also not ideal (from the environmental point of view) because the Moroccan grid is powered mainly by fossil fuels. According to the IEA, coal is the main source used for electricity generation in Morocco. In 2020, coal was responsible for 68% of the total electricity generation, followed by natural gas with 9% and oil with just 2%. Renewables make up to 18% of the total electricity supply distributed between wind 11%, solar 4% and hydropower 3% [177]. The energy sector in Morocco is undergoing a transition to reduce its reliance on imported fossil fuels and increase the share of renewables. The National Energy Strategy of Morocco has a target of 52% of electricity from renewable sources by 2030 [178].

The Souss-Massa Basin is an interesting case application for exploring RQ3 and RQ4 of this thesis for several reasons. First, it is shared between different sectors (water, agriculture, tourism, etc.) on a sub-national scale. Second, it relies on both surface and groundwater sources. Third, it aims to increase the share of renewables and accelerate the decarbonisation process.

To summarise, this thesis focuses on the sustainable management of shared water bodies. The four research questions identified in this dissertation will be explored in two contexts, the Balkans and North Africa with two case applications in each region. The remainder of this thesis is structured as follows. **Chapter 2** introduces the methodology, modelling frameworks and tools used in this thesis. The aim of **chapter 3** is to describe, discuss and interpret the results and insights obtained for each research question. Lastly, **chapter 4** provides concluding remarks, discusses the limitations of this thesis and gives some recommendations for future work.

2 Methodology

The methodology followed in this dissertation is a “mixed-methods” methodology. Which can be defined as “*the type of research in which a researcher or team of researchers combines elements of qualitative and quantitative research approaches…for the purposes of the breadth of understanding and corroboration”* [179]. Under each approach, a combination of methods or tools is used as illustrated in Figure 7. This chapter gives an overview of the methods applied and the rationale as well as an overview of the case-specific methods and scenarios. A detailed elaboration about each model structure, input data and key assumptions can be found in the appended papers. This section is complementary to the papers and presents an overall picture of the methodology used in the dissertation.

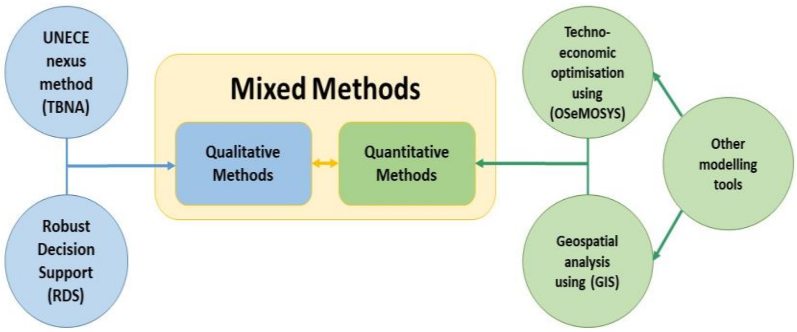

Figure 7. Overview of the methodology and methods followed in this dissertation.

2.1 Qualitative methods: (participatory approaches)

The complex nature of shared water management issues demands close collaboration with stakeholders. Therefore, stakeholder engagement is a main pillar of this research. The Transboundary Basins Nexus Approach (TBNA) developed by the UNECE was chosen among other nexus approaches due to its solid participatory approach in different settings.

2.1.1 The UNECE Transboundary Basins Nexus Approach (TBNA)

This methodology was developed in response to the need to manage interactions with a wide range of stakeholders and multiple institutions in transboundary water basins. The first edition of the methodology focused on river basins and was developed and published in 2015/2016 [29], [134]. This was later broadened and informed by the work developed in this dissertation (i.e. NWSAS) to include groundwater basins and the second edition of the TBNA was published in 2018 [30].

As described in [30], the TBNA methodology is based on six principles and carried out in six steps as shown in Figure 8. The principles of the TBNA methodology are: 1) Participatory process; 2) Knowledge mobilisation; 3) Sound Scientific Analysis; 4) Capacity building; 5) Collective efforts; and 6) Benefits and Opportunities.

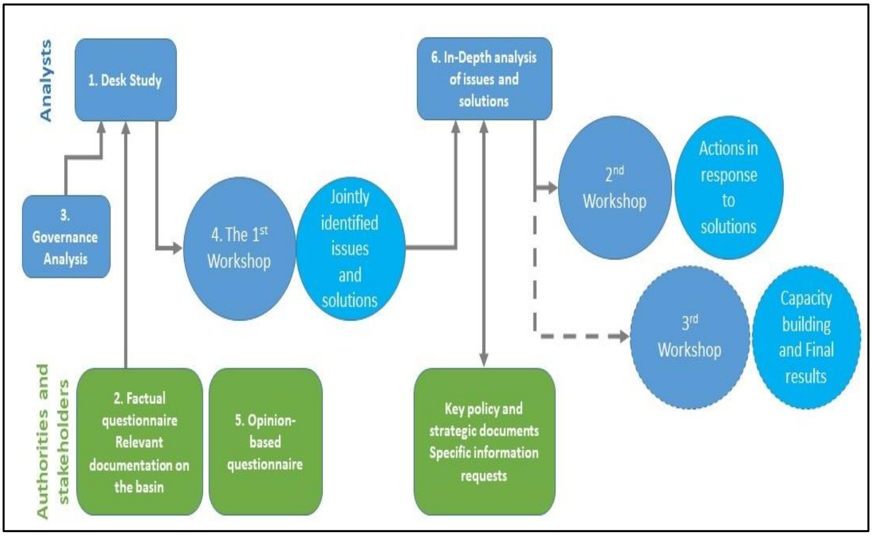

Figure 8. The TBNA assessment process.
(source: author's interpretation based on [30])

The six steps of the assessment are: Step 1) A desk study to identify the socioeconomic context of the basin; Step 2) A factual questionnaire is used to map the key sectors and key actors, and identify the main stakeholders to be involved in the following steps; Step 3) explores the strategies, policies, mandates, and responsibilities in the management of basin resources through a governance analysis. The information collected in steps 1-3 is used as input to inform the dialogue between participants, that is Step 4) the first nexus workshop which kick-offs the intersectoral and transboundary nexus dialogues and consultation. The outcome of this step is a list of basin-specific interlinkages and pressing intersectoral issues (known also as nexus issues). In step 5) an opinion-based questionnaire and a plenary discussion is used to understand the sectoral perspectives and prioritise the identified interlinkages. Finally, Step 6) focuses on developing solutions to the identified issues and quantifying them wherever possible. The in-depth analysis conducted in this step, informs the discussion in the second workshop (in some cases a third workshop is also conducted).

The TBNA assessment process is implemented in all four case applications (papers I-IV) with some changes in the aforementioned steps tailored to match the needs of each case. For example, in the Drina nexus assessment (paper I) a third workshop was conducted to validate the findings of the study. In the NWSAS assessment (paper III) national consultation workshops were conducted back-to-back with the second transboundary workshop. In the Drin assessment (paper II) a sectoral consultation meeting was conducted with energy representatives to validate the findings of the energy-water model and to overcome the issue of the misrepresentation of the energy sector in the transboundary workshops.

In all assessments, the author contributed to the implementation of the TBNA approach in different steps. This included but was not limited to, conducting the desk study, designing and preparing the material for the workshops, presenting the findings and leading discussions with stakeholders in different workshops.

2.1.2 Robust decision support - beyond the TBNA

The implementation of the TBNA approach in different contexts and the interaction with stakeholders at different levels, helped the author to notice some of the shortcomings of this approach. For example, after identification of the nexus issues, there is no clear strategy on how to prioritise them. Also, there is no clear strategy on how to evaluate and compare different solutions. More importantly, the TBNA lacks consideration of future uncertainties and how to take a decision if such conditions arise.

One approach that is widely applied in water planning in a participatory setting is the practice of Robust Decision Support (RDS) [180]. RDS was developed by Stockholm Environmental Institute (SEI) and inspired by the Robust Decision Making (RDM) framework from the RAND Corporation. The RDM is a framework for decision-making in circumstances where there is a high level of uncertainty [181].

In the Souss-Massa case (paper IV), a novel approach is designed by integrating the UNECE-TBNA approach and the RDS process from SEI. Some changes are made to both frameworks for the sake of integration and to fit the purpose and the scale of the study. For example, the RDS explores sector-specific goals, critical uncertainties and policy/infrastructure strategies. The TBNA follows with its solid participatory approach and groups stakeholders across sectors and guides them to see how the actions and/or the plans of the sectors had intended and unintended implications across sectors.

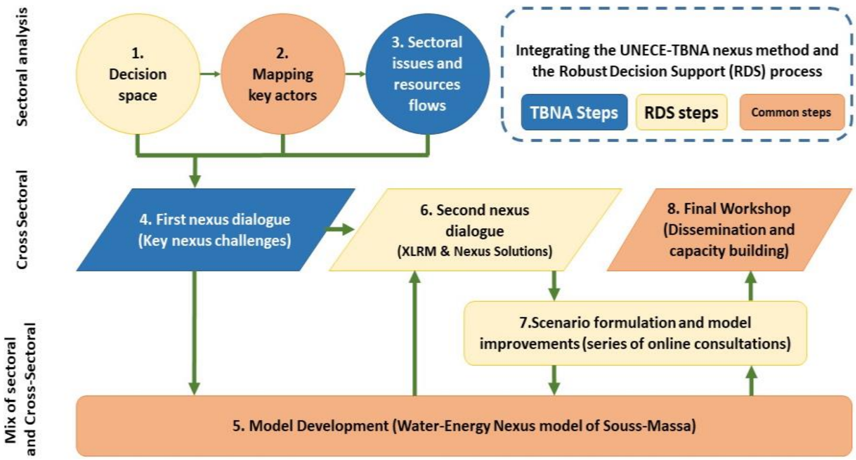

Figure 9. Schematic diagram of the enhanced participatory nexus methodology

As shown in Figure 9, the integration of the two approaches results in eight steps. The first step focuses on identifying the decision space and the basin socioeconomics. This includes the current state of the sectors of interest, main strategic goals and development policies. The second step maps the key actors (in each sector) involved in the process. The third step looks into the sectoral issues and resource flows using quantitative indicators (wherever possible). Steps 1 to 3 take a sectoral perspective and are conducted in a “desk study” format. The fourth step is the first nexus dialogue with stakeholders or the “problem formulation workshop”. In this step, the analysts interact with representatives from the agriculture, water, energy and environment sectors who come from different backgrounds (i.e. government, academia, Non-Governmental Organisations (NGOs) and the private sector). The main outcome of this step is the common understanding of the WEF nexus approach and the mapping of the “key nexus challenges” in the basin. The fifth step uses analytical modelling tools to study the nexus interdependencies and explore various solutions in more depth. The sixth step is the second nexus dialogue, which takes the stakeholders through the eXogenous, Levers, Relationships and Metrics of performance (XLRM) process [181] to formulate potential solutions and to design the metrics used to evaluate the robustness of the solutions. The seventh step is model refinement which can be formulated as a series of consultation meetings and running ensembles of scenarios to meet the metrics of performance developed in the previous step. The eighth and final step is the dissemination of the study findings and the capacity-building activity based on the analytical tools.

The four dimensions of the XLRM process (step 6) are:

- X (e**X**ogenous factors): represents factors outside the control of the actors but which have the potential to influence the outcomes. The vulnerability assessment or the (vulnerability-impact) mapping exercise is used to identify the vulnerability of the system to the key factors and their relative impact.

- L (**L**evers): represents the specific actions that are available to the actors as they seek to improve conditions or outcomes in the face of future uncertainty. Through stakeholders' consultations, several scenarios are designed incorporating different levers.

- R (**R**elationships): the models used to develop the relationships between the sectors.

- M (**M**etrics of performance): by which actors evaluate the outcomes of a specific scenario.

Integration of the TBNA and RDS approaches has been carried out for the first time, and it could be argued that this is one of the contributions of this dissertation to the nexus methodologies and approaches. Additionally, this is the first study to implement the UNECE-TBNA methodology at a sub-national level instead of on a transboundary scale which is the standard application of the TBNA.

2.2 Quantitative methods: modelling tools and techniques

The interactions between the WEF nexus systems are complex. Qualitative approaches are not enough to gain a deep understanding of the different interactions and their implications. Therefore, the use of quantitative methods is crucial in such a context.

The selection of the modelling tool(s) is based on each case application and the related research questions. In this dissertation, as illustrated in Table 6, more than one modelling tool is often used to capture the different dynamics of the resource systems. Two types of modelling tools are used to model the energy system. The first is the Open Source Energy Modelling System (OSeMOSYS) [182] and the second is the Geographic Information System (GIS). OSeMOSYS is used for the Drina and Drin case applications where the long-term power system outlook for each of the riparian states is modelled. This means developing national electricity supply system models for six counties in the Balkans. Climate and hydrological inputs are taken from external models (e.g. E-HYPE) and used to provide OSeMOSYS with the changes in water availability in the Drin River Basin under different climate projections. For the NWSAS and Souss-Massa cases, the focus is more on the agricultural activity and energy use for groundwater pumping in the selected basins. Therefore, a spatial approach is taken and an energy-water-agriculture model is developed for each case. In the NWSAS, the three systems of agriculture, water and energy are integrated into one model using GIS and Python (a programming language) [183], while in the Souss-Massa case, water and agricultural aspects are detailed using the Water Evaluation And Planning system (WEAP) [184]. Only the energy aspects are modelled using a GIS-based energy model and processed using Python. The author led the development of all models except WEAP which was developed by project partners from SEI.

Table 6. Overview of the modelling tools and how different systems are considered in each case application

	Case Applications (Paper)			
	Drina (I)	**Drin (II)**	**NWSAS (III)**	**Souss-Massa (IV)**
Energy	Long-term Energy model (**OSeMOSYS**)		Energy demand for agri-uses is estimated using a **GIS**-based energy model.	
Water	A simplified hydrological representation of the basin is introduced in **OSeMOSYS**.	**OSeMOSYS** is fed with outputs from the **E-HYPE** hydrological model to represent water availability in the Drin Basin.	Monthly irrigation demand is estimated using **GIS**.	Water demand, supply and transmission are modelled using **WEAP**
Agriculture/ Food	-	-	Cropped areas and selected crops are used to estimate irrigation demand using **GIS.**	Cropped areas are specified for the four general crop types (cereals, fodder, trees and vegetables) in **WEAP**.
Climate	Changes in emissions are estimated for two scenarios (with/without energy efficiency)	Outputs of E-HYPE are used to represent RCPs (2.6, 4.5 & 8.5). These are then fed into **OSeMOSYS.**	-	Two climate conditions are implemented in **WEAP:** historical trends and extended droughts.

2.2.1 Energy system representation using OSeMOSYS

OSeMOSYS is a long-term energy system optimisation framework. It is an open-source tool with a flexible structure, which makes it suitable for a wide range of applications at various scales. The typical application is the modelling of the electricity supply system, however, other applications such as heating systems, transport, job creation and CLEWs-nexus [32], [124], [185], [186] can also be modelled in OSeMOSYS. The scale of applications also varies from national to continental and global levels [187]–[191]. OSeMOSYS is one of a few open-source tools that are considered mature enough for policy analysis [192].

The building blocks of OSeMOSYS are a) technologies (e.g. power plants) and b) commodities or energy carriers (e.g. electricity). As shown in the simplified Reference Energy System (RES) in Figure 10, technologies are represented as boxes and commodities are shown as lines. The flow goes from left to right, from primary energy sources such as natural gas, coal, water, etc., which feed the power plants, while the generated electricity is then transferred using the transmission and distribution network to satisfy the final energy demand either in the form of electricity or some other form of demand (depending on the application).

Like other modelling frameworks, OSeMOSYS is a data-intense framework. The user needs to feed OSeMOSYS with different types of inputs. The exogenously calculated demand projections, the list of power supply technologies, the techno-economic characteristics of each power plant and cost projections, are just a few examples. The model is restricted by a set of user-defined constraints used to reflect reality, such as operational requirements, governmental policies, socioeconomic constraints, and environmental or climate constraints [182].

OSeMOSYS is chosen in this dissertation for several reasons. First, for its flexible structure that allows the development of a “simplified hydrological system”[4] within the electricity supply framework and to study new operational rules for hydropower operation. Second, it is a long-term modelling tool suitable for exploring the long-term impact of climate change and the proposed changes in hydropower operation. The short-term modelling that looks at the hourly dispatch and balancing of supply and demand is deemed out of the scope of this analysis. Third, it is an optimisation tool (cost-minimisation) which means it proposes changes to the electricity generation mix to minimise the overall system cost. Additionally, the open-source nature of OSeMOSYS makes it fit the context of shared water management where transparency of the modelling structure, input data and assumptions is an important aspect. Furthermore, it is a driver for open-source and reproducible research.

[4] More precisely this is a techno-economic representation of water availability along a cascade of hydropower plants. OSeMOSYS input parameters and constraints are used to mimic river segments, maximum water flow and minimum water flow in each river segment for each week of the year. Other hydrological aspects (e.g. precipitation, run-off, etc.) were not considered in this representation.

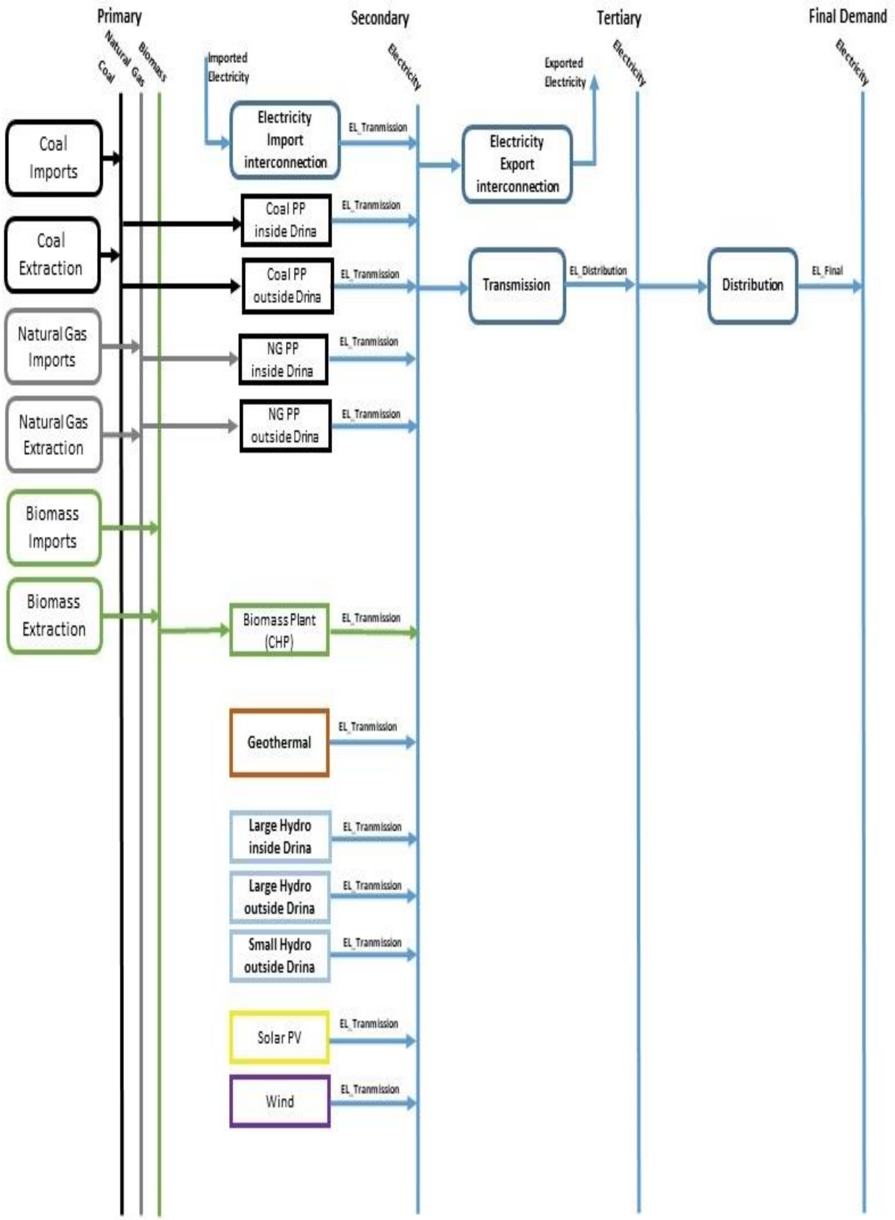

Figure 10. A simplified Reference Energy System (RES) representing the OSeMOSYS model structure for the Drina Basin (paper I).

That being said, there are several limitations that should be taken into consideration when analysing the model results. OSeMOSYS assumes perfect market conditions with perfect competition and foresight. This means that the model assumes that market participants provide energy at a marginal production cost. It also assumes that all participants are fully aware of all present and future conditions affecting the costs of energy production or purchase. More importantly, investment and generation decisions in OSeMOSYS are all based on cost-minimisation (after all other constraints have been satisfied). Other aspects such as demand response, geopolitical constraints, geospatial distribution, social behaviour and security concerns do not impact the model outputs unless they are first translated into cost constraints.

2.2.2 Energy system representation using GIS

The second type of energy model developed in this dissertation is the GIS-based model. This type of model is useful for evaluating activities that interact with natural resources and physical conditions, which are dependent on the location. Avoiding the aggregation of the spatial dimension provides more realistic and relevant insights for decision-makers in such a context.

The work developed in this thesis took the Open-Source Spatial Electrification Tool (OnSSET) [193] as a starting point but changed the focus from electrification to productive uses of electricity, more specifically to estimate the electricity requirement for groundwater pumping. To achieve this, modelling of the agricultural and water aspects is a necessity. A spatial modelling approach is chosen for this part of the dissertation since the focus of the analysis is on sub-national and regional scales. Also, the agricultural activity is often rural and takes place in locations far away from typical demand concentration centres such as major cities. This makes modelling of the national electricity system less relevant for this type of application. Additionally, a GIS-based approach is chosen to capture important spatial differences such as groundwater depth, elevation differences and renewable energy sources in each location.

ARC-GIS and Q-GIS software are used for the purpose of this dissertation. Several site-specific information was collected and processed in GIS for the NWSAS region and the Souss-Massa Basin (papers III-IV). For example in the Souss-Massa case shown in Figure 11, the process starts by collecting various inputs such as inputs from the participatory process, inputs from the water model (WEAP), from GIS datasets (e.g. administrative boundaries, cropland area, elevation, solar irradiation and others) and inputs related to the technical specifications of different technologies (e.g. costs, efficiencies, lifetime and others). The Python programming language is then used to process all the collected inputs and to develop the mathematical relationships for each activity or module. Modular codes are developed for each part of the analysis to make it easier to use and maintain the model. Taking the example of Souss-Massa, the first module of the energy model estimates the electricity requirements for four activities: Groundwater pumping, surface water pumping, seawater desalination and wastewater treatment and reuse. While the second module explores various decarbonisation options for the agricultural sector in Souss-Massa.

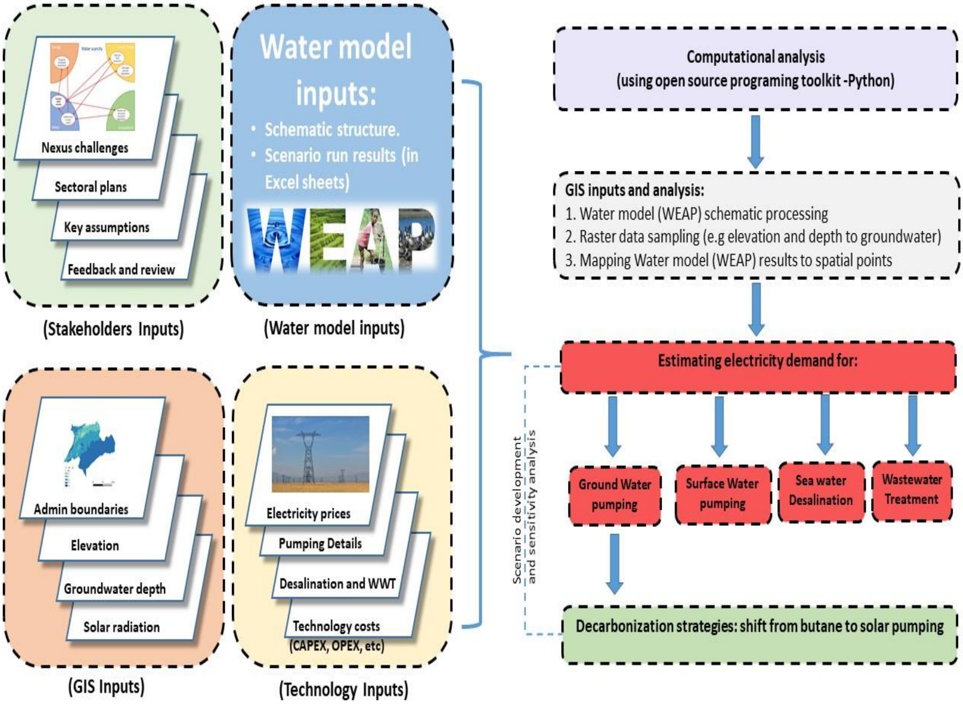

Figure 11. Overview of the modelling structure showing the key inputs to the energy model and different energy modules.
(Paper IV, The Souss-Massa Basin in Morocco).

In the NWSAS case, the water and agricultural aspects are included in the model. Therefore the first module is about cropland calibration, the second is focused on estimating irrigation water requirement, the third is about estimating the electricity requirement for groundwater pumping and the last module is dedicated to estimating the least-cost electricity supply option based on the Levelised Cost of Electricity (LCOE). The following paragraphs give an overview of the electricity requirements calculation and the LCOE calculation.

Energy for pumping (kWh) is expended when a unit volume (m^3) of water passes through a pump during its operation [194]. The electricity demand depends on the efficiency of the pump, the pipeline diameter, the pipe material roughness or friction factor, and the volumetric demand for water. As shown in the following function for electricity demand, E_D (kWh):

$$E_D = f(d, Q, P, t, f_l) \quad \text{Equation 1}$$

where *d* is the distance through which the water is to be lifted, *Q* is the required volumetric amount of water for pumping, *P* is the pressure required at the point of use, *t* is the time over which the water is pumped (assuming a constant head), and f_l is the friction loss along the distance *d* within the distribution system.

The calculation of electricity demand (ED_{gw} in kWh) for pumping water from groundwater resources, can be calculated as follows:

$$ED_{gw}(kWh) = [Seasonal\ scheme\ water\ demand\ m^3 * TDH_{gw}(m) * 0.00272]/PP_{eff}(\%)$$

Equation 2

where *Seasonal scheme water demand (*m³*)* is the total volume of water requiring pumping over a selected season as will be shown in the following sections. The constant 0.00272 is simply water density times gravity and has the unit kWh/m³ per m of lifting. TDH_{gw}*(mm)* represents the Total Dynamic Head and PP_{eff} *(%)* accounts for the Pumping Plant efficiency. The TDH is estimated using the following equation:

$$TDH_{gw}\ (m) = EL(m) + SL(m) + OP(m) + FL(m) \quad \text{Equation 3}$$

where *EL (m)* is the Elevation Lift, the sum of the depth to the groundwater level of water and of the water table or drawdown. *SL (m)* expresses the Suction Lift which is assumed to be zero in groundwater vertical pumping. *OP (m)* stands for Operating Pressure and accounts for the pressure needed based on the application and conveying system. And *FL (m)* represents the Friction Loss in the piping systems. In this indicative study, and for the sake of simplicity, the TDH is assumed to equal the water table depth (m) since other parameters were assumed equal to zero as no data was available on the average conveyance system or the piping systems.

The Pumping Plant efficiency is given as:

$$PP_{eff}(\%) = fuel\ efficiency * power\ unit\ efficiency * transmission\ efficiency * pump\ efficiency * 100\%$$

Equation 4

Finally, the overall electric power for groundwater pumping is calculated using:

$$PD_{gw}\ (kW) = 9.81 * discharge\left(\frac{m^3}{s}\right) * TDH_{gw}(m)PP_{eff}(\%)$$

Equation 5

Where: *discharge (m^3/s)* is the *peak scheme water demand (l/s)* expressed in m^3/s.

The LCOE is a life-cycle cost concept that accounts for all physical assets and resources required to deliver one unit of electricity output. It accounts for all the expenses (investment costs, operating and maintenance costs, and fuel costs) as well as the revenues generated from electricity generation sales over the lifetime of the power plant or the small-scale installation [195].

$$LCOE = \frac{\sum_{t=1}^{n}\frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}}$$

Equation 6

Where I_t: is the investment expenditure for a specific system in year t, $O\&M_t$: are the operation and maintenance costs, F_t: the fuel expenditure, E_t: the generated electricity, r: the discount rate, n: the lifetime of the system.

The full code for each application is available on a GitHub repository [196], [197] and a detailed description of the mathematical relations used in the energy calculations can be found in the appended papers.

2.2.3 Agricultural system representation (Evapotranspiration and crop water requirement calculations)

In this dissertation, crop evapotranspiration (for the NWSAS region, paper III) is estimated using the FAO-56 Penman-Monteith method [198]. This method estimates the reference crop evapotranspiration based on monthly climate data. According to FAO-56, reference crop evapotranspiration (ETo) is defined as the "*evapotranspiration of a hypothetical reference crop with a height of 0.12 m, a surface aerodynamic resistance of 70 s m-1 and an albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water*" [198]. The formula describing this is:

$$ET_o = 0.048R_n - G + 900T + 273u_2e_s - e_a + 1 + 0.34u_2$$

Equation 7

Where; ETo is the reference evapotranspiration (mm day^{-1}), Rn is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2m height (°C), u_2 is the wind speed at 2m height (ms^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), e_s - e_a is the saturation vapour pressure deficit (kPa).

To be able to automate this calculation for a large region such as the NWSAS, a Python library called "Pyeto" [199] is used to calculate meteorological parameters from climate data, which are then used to calculate the reference evapotranspiration.

Due to the monthly variations in crop water requirement, the reference evapotranspiration is not enough to represent crop water requirements. The crop coefficient (Kc) adjusts the monthly water requirements based on the crop calendar. Crop calendar and crop coefficient data for each crop are taken from the literature as shown in Table 7. This data is then spatially and temporarily (monthly and yearly) aggregated to represent the variation in Kc values in each growing season and the resulting change in crop water requirement (ET_c):

$$ET_c = ET_o * k_c$$

Equation 8

Local experts from the NWSAS countries are consulted to understand the distribution of the selected crops in each province.

Table 7. Crop calendar and crop distribution in the NWSAS region

Growing cycle		Dates	Vegetable	Olives
Planting	init_start	01/11	01/11	01/03
	init_end	30/03	25/11	30/03
	Kc ini	0.56	0.5	0.45
Growing	dev_start	31/03	26/11	31/03
	dev_end	04/05	31/12	30/06
	mid_start	05/05	01/01	01/07
	mid_end	30/09	07/02	31/08
	Kc mid	0.7	1	0.55
Harvesting	late_start	01/10	08/02	01/09
	late_end	31/10	28/02	30/11
	Kc end	0.56	0.8	0.6
Sources		[200],[201]	[198]	[202]
Distribution in the NWSAS provinces (% of irrigated cropland area)		In most provinces: date palm (50%) and vegetables (50%) except: Gharyan (Libya): olives (70%) and vegetables (30%) Jufrah (Libya): dates (70%) and vegetables (30%)		

This means that for the irrigated area within each grid cell (1km * 1km) the model uses different types and shares of the crops cultivated to calculate the daily and monthly irrigation requirements taking into account the variations in temperature, wind speed and the growing phase of each crop.

For the Souss-Massa case, this calculation is carried out in WEAP using a similar approach based on the FAO-56 Penman-Monteith equation.

2.2.4 Water system representation

The representation of the water system varies from case to case in this dissertation. For the river basins (paper I and paper II) the water system is introduced as a simplified hydrological system within OSeMOSYS. For the NWSAS Basin, the representation of the water system is developed to estimate the irrigation water demand for selected crops. While in the Souss-Massa Basin, a water balance model (WEAP) is used to represent water demand, supply and transmission and distribution. As mentioned earlier, the Souss-Massa WEAP model was developed by other analysts and the author used the outputs of WEAP to run the energy module. Apart from WEAP, the author developed the water module in other models as described in the following paragraphs.

Introducing a simplified hydrological system within OSeMOSYS means that the river system is divided into tributaries and river segments. The volume and the flow in each river segment are constrained by the historical maximum flow extracted either from gauging stations [203] (e.g. the Drina river case, paper I) or from hydrological models (e.g. the Drin river case, paper II). This means that the water flow in the river system is simulated within the energy modelling framework to have better water availability for hydropower plants. Additionally, the cascade of reservoirs and hydropower plants in each river basin is detailed as illustrated in Figure 12. This representation is dictated by the structure of OSeMOSYS (based on technologies and commodities). The river segments upstream and downstream of a power plant are represented in an aggregated way, as a water source (a box or technology in OSeMOSYS) providing or receiving a certain water volume flow. The water flows from the upstream river segment to the dam reservoir. The water available in the dam can either be fed to the hydropower plant (when this needs to generate power) or it can be stored (when the dam is not full), or the third path is to release it through a spillway. The operational rules dictate to what extent the dam can be discharged (usually down to the minimum storage level) and how much it can be filled up which is usually the maximum level allowed by the buffer volume used for flood containment.

The Europe-Hydrological Predictions for the Environment (E-HYPE)[5] is a hydrological model from the Swedish Meteorological and Hydrological Institute (SMHI) [204]. The model is forced by daily precipitation and temperature and then calculates flow paths in the soil based on several parameters such as snowmelt, evapotranspiration, surface runoff and infiltration [204]. For the Drin Basin case (paper II) the outputs of the E-HYPE model are used to represent the volume and flow in each river segment under different scenarios.

[5] The HYdrological Predictions for the Environment (HYPE) distributed hydrological model when applied across Europe, is called (E-HYPE) [204].

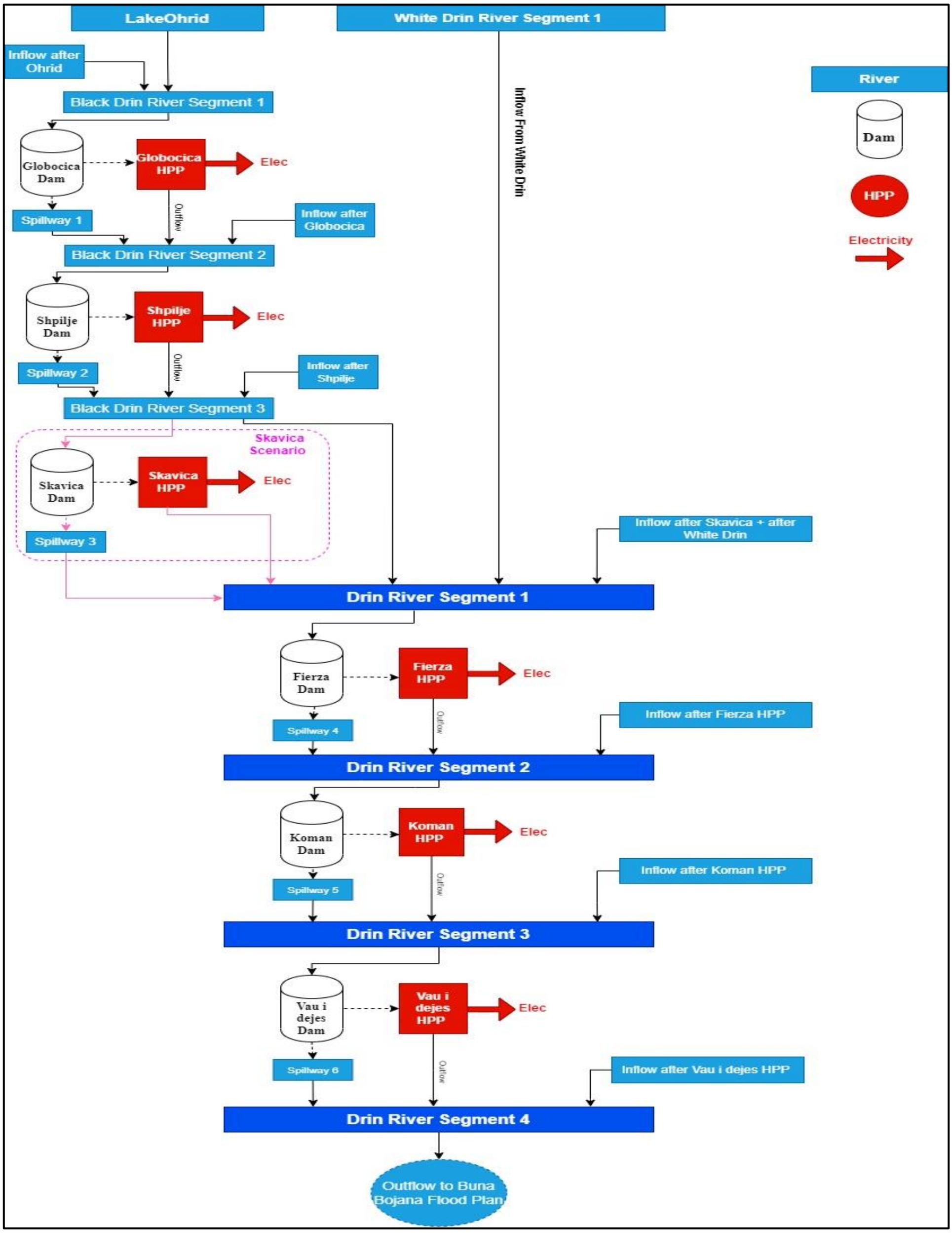

Figure 12. Structure of the hydropower cascade in the Drin River Basin, as represented in OSeMOSYS.

In the NWSAS case (paper III) the model includes a module to estimate the irrigation water requirement. The water supply of the irrigation scheme must be equal to or greater than the demand throughout all the growing stages of the crop(s) planted. The water requirements depend on the crop water requirements (expressed as ETc), climatic and land conditions, and the efficiency of the irrigation system.

The reference crop evapotranspiration (ETo), crop coefficient (Kc) and the crop water requirement (ETc) for each crop in each month are calculated as shown in the previous step (sub-section 2.2.3).

The irrigation water need (IN) is calculated based on the crop water requirement (ETc) and the effective rainfall (eff). Other parameters such as the leaching requirements and the available water content in the root zone at a given point were assumed negligible in an arid climate [205] such as the NWSAS region:

$$IN = ET_c - eff$$ Equation 9

where IN is the irrigation water need (mm day^{-1}), ETc is the product of ETo and kc as shown earlier (mm day^{-1}), eff is the effective rainfall (mm day^{-1}).

Effective rainfall represents the amount of rainwater that can be retained in the root zone and can be used by a plant. An empirical correlation is used to calculate the effective rainfall on a monthly basis based on the literature [206].

The monthly scheme water demand (m^3) refers to the amount/volume of water needed over a month, taking into account the water losses in the distribution system (distribution efficiency) and field application (application efficiency) [205]. Furthermore, it is one of the key parameters for estimating the electricity demand required for pumping over one month.

$$Monthly\ scheme\ water\ demand\ (m3) = \frac{Monthly\ crop\ water\ requirement\ (m3) x\ Irrigated\ area\ (ha)}{Application\ efficiency\ \ x\ Distribution\ efficiency}$$

Equation 10

Peak crop water demand (PWD) is another important design criterion of an irrigation scheme because it determines the size of the required pump and the distribution system and therefore the operational power demand for the irrigation scheme. The maximum discharge is the rate at which water must flow to meet peak demand [205]. Pipes, canals or channels must be large enough to carry this discharge and the pump and power unit must be capable of delivering the discharge at the required pressure. Due to the high variation in demand throughout the season, the peak requirement might be at least double the average daily water need.

After this overview of the various methods and systems represented in this dissertation, the following section gives more details on each case application, discussing scenarios, data sources and key assumptions.

2.3 Elaboration of the case applications (scenarios, data and key assumptions)

The research methods described above are applied to the different case applications to explore different questions. In each application, a combination of qualitative and quantitative methods is applied. Additionally, each case has its unique narrative and set of scenarios that build up that narrative. This section gives an overview of the adopted methods in each application, describes the scenarios, and highlights the key assumptions and data sources. Further details on the methods and input data can be found in the appended papers.

Before considering the case applications in more detail, it is worth highlighting the importance and relevance of the participatory process in this dissertation. The participatory process or the nexus dialogue with the stakeholders in each basin is an imperative pillar of the quantitative approach or model development. Many of the case-specific techno-economic parameters are either obtained from or validated by local experts as will be shown later. However, when case-specific data is not available, generic data from international sources like the IEA, IRENA and FAO is used. The methodology and the open-source nature of the models developed in this dissertation, allow future improvements to be made whenever better data is available.

All the case applications implemented different scenarios as a strategy for exploring the targeted research question(s). The father of scenario planning, Herman Kahn defines a scenario as "*a set of hypothetical events set in the future constructed to clarify a possible chain of causal events as well as their decision points*". Scenarios can also be defined as alternative futures resulting from a combination of trends and policies [207]. The use of scenarios to clarify thinking about the future was first applied systematically after World War II for military purposes. In the last few decades, the use of scenarios has increased significantly due to the greater uncertainty and complexity of the systems examined [207] such as nexus systems. Needless to say, scenarios do not forecast the future but rather create a set of plausible futures [208].

2.3.1 The Drina River Basin

Paper I is aimed at addressing research question 1 on the role of the energy sector in motivating cooperation in shared water basins. The Drina River Basin is chosen as the case application to explore this question. The engagement with stakeholders in the participatory nexus process (sub-section2.1.1) goes arm in arm with the model development process. Each process informs the other. For example, stakeholders provide data and validate assumptions and findings while the model provides insights for the policy-making process.

A multi-country model of the three countries (Bosnia and Herzegovina, Montenegro, and Serbia) sharing the Drina Basin is developed using OSeMOSYS. The Drina-OSeMOSYS model introduces a detailed representation of the cascade of the hydropower plants in the Drina Basin to enable studying of different cooperation setups. This required introduction of a hydrological system within OSeMOSYS (Figure 13). Such a structure allows exploration of the impact of upstream hydropower plant operation on downstream plants because all hydropower plants rely on the Drina river flow.

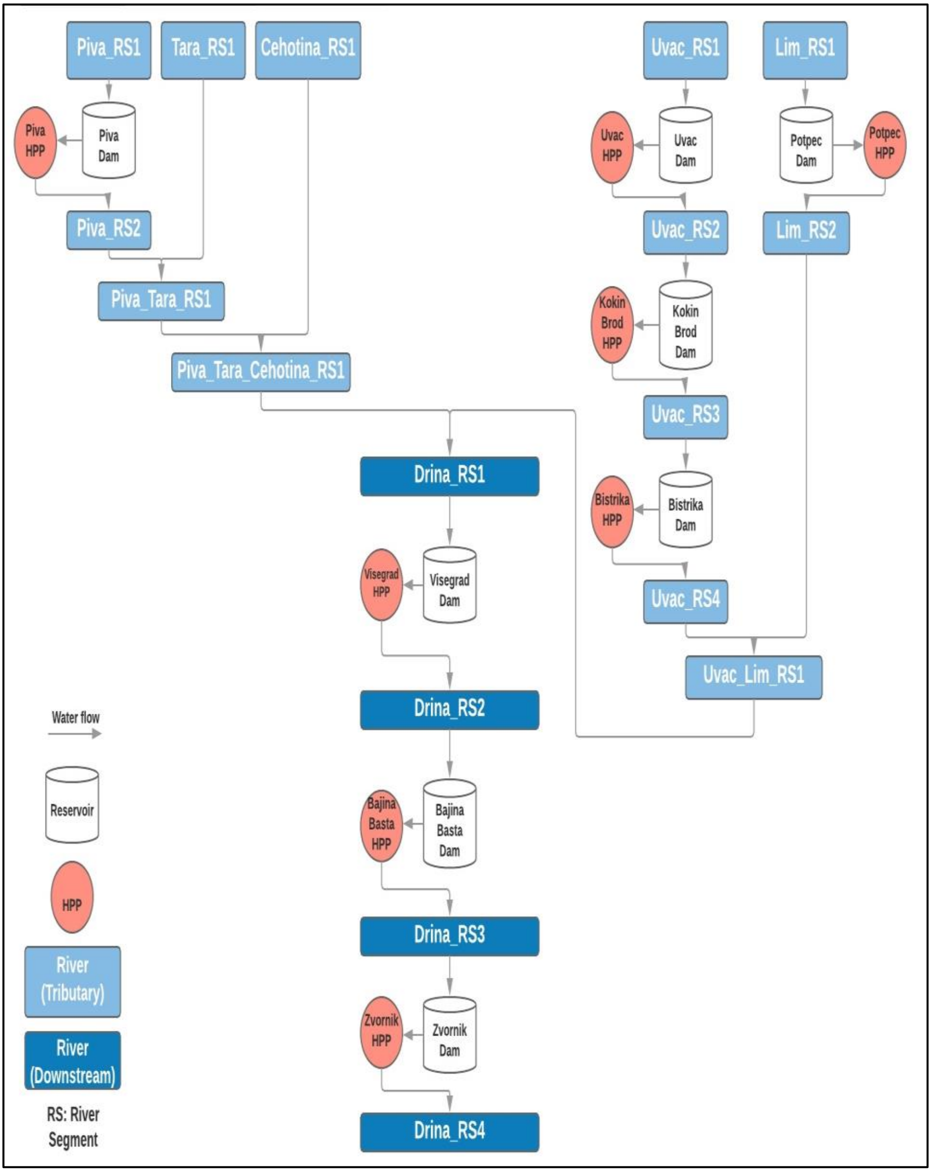

Figure 13. Schematic representation of the cascade of hydropower plants in the Drina River Basin.

For this study, three scenarios are analysed:

- **The base scenario (BASE)**: represents the current status of low cooperation and what may happen in the coming decade under this scenario. Piva hydropower plant has the largest storage capacity (Table 3) and its operation affects the flow regime downstream. Other upstream hydropower plants have a relatively lower impact. Therefore, and after consultation with stakeholders, this scenario is designed to focus on the impact of Piva on the three downstream hydropower plants. This scenario simulates an extreme historical situation assuming a minimum outflow from Piva for one month of the year. The downstream power plants and the rest of the power system have to accommodate this operation.
- **The cooperation scenario (COP)**: the constraint imposed in the previous scenario is removed and no power plant operates "independently". In this scenario, all hydropower plants operate optimally to achieve the least-cost electricity generation mix for the whole basin and region.
- **Increased electricity trade scenario (COP_TRD):** This scenario has the same structure as the cooperation scenario. Additionally, it explores the possibility for the three countries in the Drina River Basin magnifying the benefit of cooperation and low-cost hydroelectricity by improving interconnections and the trade of electricity between them and with neighbouring countries. More specifically, in this scenario, the model is allowed to increase the trade beyond the maximum historical trade that occurred between 2008-2014 (shown in Table 8) and is used as a constraint in other scenarios.

Table 8. Maximum historical electricity trade for the Drina riparian states (2008-2014) [209]

	Bosnia and Herzegovina		Montenegro		Serbia	
	Export to	**Import from**	**Export to**	**Import from**	**Export to**	**Import from**
Albania	-	-	2,691	359	315	1,047
Bosnia and Herzegovina	-	-	628	3,230	2,378	614
Bulgaria	-	-	-	-	427	2,621
Croatia	4,927	2,526	-	-	2,061	294
Hungary	-	-	-	-	952	2,650
Montenegro	3,230	628	-	-	1,595	1,450
N. Macedonia	-	-	-	-	2,683	59
Romania	-	-	-	-	440	3,215
Serbia	614	614	1,450	1,595	-	-

2.3.2 The Drin River Basin

Paper II continues to explore the role of the energy sector in supporting shared water management (RQ1). In this paper, the focus is on extreme climate conditions such as floods. This paper also explores the impact of climate change on the security of electricity supply in shared water basins and the role of variable renewable energy sources (RQ2). This study again focuses on the Balkans, but this time the Drin River Basin is studied.

Building on the methodology and the lessons learned in paper I, this paper also uses OSeMOSYS and introduces a hydrological system (Figure 12) for an in-depth study of the cascade of hydropower plants in the Drin Basin. This includes two cascades of two and three large hydropower reservoirs on the Black Drin and the Drin river respectively. Additionally, provision is made for a planned hydropower plant in Albania (Skavica). The volume and flow in each river segment are constrained based on E-HYPE model outputs for a reference case and climate change scenarios.

Beyond the hydrological representation of the basin, the Drin-OSeMOSYS model encompasses the entire electricity supply system of each of the four riparian states (North Macedonia, Albania, Montenegro and Kosovo). This means all the current and potential electricity supply technologies including hydropower plants (inside and outside the basin), thermal plants, non-hydro renewables (solar and wind) as well as electricity trade interconnectors. Each group of supply technologies is represented in an aggregated form, except for the five hydropower plants in the Drin Basin. The time domain of the model is between 2020 and 2050 and each year is split into 52 weekly time steps. A weekly temporal resolution is considered an adequate representation of the water variability with a manageable computational time.

National projections until 2035 are used to extract the electricity demand for each country [210] [211] [212] with additional extrapolation until 2050 (based on the average annual growth rate of electricity demand 2015-2050) [213]–[216]. The load profile is obtained for three seasons (winter, summer and intermediate) [210] [211] [212] and averaged to weekly resolution. Furthermore, for each riparian state, hourly capacity factor[6] data for solar and wind technologies are extracted from the "Renewables. Ninja" dataset [217], [218] and averaged to weekly time resolution. This makes the capacity factor of the VRE technologies consistent with the weekly demand profile. Spatial differentiation between the inside and outside of the Drin Basin is considered for a better spatial representation of the VRE capacity factor. The model then calculates the least-cost electricity supply mix and the investments needed in new capacity given the techno-economic characteristics of supply technologies as shown in the following table.

[6] Capacity Factor: is the ratio of actual annual output to output at rated capacity for an entire year. It is a measure of a power plant's actual generation compared to the maximum amount it could generate in a given period without any interruption [2], [3].

Table 9. Techno-economic characteristics of the power supply technologies.

Type	Capital Cost* (million USD "mUSD")				Variable Cost	Fixed O&M	Operational Life	Capacity Factor
	AL	MK	ME	XK	(mUSD /TWh)	(mUSD /GW)	(Years)	(%)
Large Hydro - Dam (New)	1,169 - 3,092**	2,552	3,453	2,240	NA	3.4	50	36-39
Medium Hydro - Run of river	NA	2,355	2,355	NA	NA	3.4	50	26-29
Small Hydro	NA	NA	NA	NA	NA	3.4	50	11
Solar PV	905	975	900	2,128	NA	35.5	20	varies
Wind	1,288	1,700	1,866-2,191	1,802	NA	29	25	varies
Coal Power plant - Existing	NA	NA	NA	NA	4.18	29	30	65
Coal Power plant - New	NA	1,555	1,490	3,000	5.18	29	30	70
CHP - NEW	NA	733	NA	NA	1.58	9.2	30	65
Combined Cycle - New	1,501	1,232	NA	NA	1.58	9.2	30	65

***** Capital costs are based on announced projects in each country. For (Medium hydro – Run of river), capital costs are based on the average of 3 projects in North Macedonia.

** 1,169 (Kalivac HPP) – 3,092 (Skavica HPP)

Sources: [219] [149] [152] [220] [221] [222] [223] [224] [225] [226]

To achieve the objectives of this study and those that emerged through the nexus dialogues from the participatory process with stakeholders (sub-section 2.1.1), three sets of scenarios are developed:

- **Reference (REF) scenario:** This scenario approximates the present conditions in the basin. It assumes that the water availability in the basin is similar to the levels observed in recent historical records (1981-2010). It also represents the current situation of the electricity system taking into account all the committed projects in the Drin riparian states.
- **Climate Change (CC) scenarios:** changes in temperature and precipitation, among others, affect water availability in the basin. This scenario is based on hydrological data from SMHI and the outputs of the hydrological model (E-HYPE v3.1.2) [227]. E-HYPE is driven by inputs from different Global Climate Models (GCMs) and Regional Climate Models (RCMs). For each combination of GCM and RCM, E-HYPE produces projections for the river flow under each RCP[7] (2.6, 4.5 and 8.5) as shown in Table 10. In this dissertation, an ensemble of the mean value is generated for each RCP resulting in three sub-scenarios. The three sub-scenarios represent changes in the river discharge in the Drin Basin for the period 2020-2050 and are used to explore the impact in terms of changes in electricity generation.
- **Flood protection (FP) scenarios:** In this set of scenarios, new operational rules are suggested to improve flood management in the basin. The operation of the dams is

[7] The RCPs are a scenario set containing emission, concentration and land-use trajectories. They provide future time series concentrations and emissions of greenhouse gases which are used by climate modelers to run climate models. Four RCPs were introduced and named according to the radiative forcing target level for 2100, a very low forcing level (RCP2.6), two medium stabilisation scenarios (RCP4.5/RCP6) and one very high baseline emission scenario (RCP8.5) [228]. SMHI and E-HYPE data uses one medium scenario (RCP4.5) only.

currently regulated by operational rules that were set in the 1980s [229]. The proposed operational rules in this dissertation increase the buffer volume in the two dams (Spilje and Fierza) by 5% and 20%[8] in the wet season (from October to May). This means increasing the free volume in the dam reserved for flood control (buffer volume) at the expense of reducing the water storage volume used for electricity generation. By doing so, the trade-offs between security of electricity supply and flood mitigation can be quantified.

Table 10. Climate model data used in the hydrological model E-HYPE [230]

Hydrological Model	RCP	Global Climate Model (GCM)	Regional Climate Model (RCM)	Period (input dataset)	Period (adjusted in the model)	Institute
E-HYPE v3.1.2	2.6	EC-EARTH	RCA4	1970-2100	2020-2050	SMHI
		MPI-ESM-LR	REMO2009	1951-2100	2020-2050	CSC
	4.5	EC-EARTH	RCA4	1970-2100	2020-2050	SMHI
		EC-EARTH	RACMo22E	1951-2100	2020-2050	KNMI
		HadGEM2-ES	RCA4	1970-2098	2020-2050	SMHI
		MPI-ESM-LR	REMO2009	1951-2100	2020-2050	CSC
		CM5A	WRF33	1971-2100	2020-2050	IPSL
	8.5	EC-EARTH	RCA4	1970-2100	2020-2050	SMHI
		EC-EARTH	RACMO22E	1951-2100	2020-2050	KNMI
		HadGEM2-ES	RCA4	1970-2098	2020-2050	SMHI
		MPI-ESM-LR	REMO2009	1951-2100	2020-2050	CSC

[8] A range of sensitivity scenarios are explored for a 5%, 10%, 15% and 20% increase of the buffer volume. However, since the changes were very small, only the result of the 5% and 20% increase are shown and discussed in the dissertation.

2.3.3 The NWSAS

In paper III, the focus changes from the wet climate in the Balkans to the arid climate in North Africa and from surface water (rivers) to groundwater. This paper aims to explore the benefits of adopting an energy-water-agriculture nexus approach in shared groundwater management, especially in water-scarce areas (RQ3). It also focuses on accelerating the low-carbon transition in the agricultural sector (RQ4).

The participatory process involved interaction with stakeholders from different sectors (agriculture, water, energy and the environment) and the three countries (Algeria, Tunisia and Libya) [231]. The process, to which the author contributed to design and implementation, resulted in the identification of the key challenges in the basin and the priority questions to be quantified. The author then led the development of a GIS-based and integrated energy-water-agriculture nexus model customised for the NWSAS Basin to address the following priority questions:

1. What is the monthly irrigation requirement in each province?
2. What would be the impact of improving the efficiency of irrigation systems?
3. What is the electricity requirement associated with pumping?
4. What would be the least-cost electricity supply option in each location to meet the estimated energy requirements?
5. What changes in technology cost and subsidy levels would be needed to make renewable technologies more competitive in the region?

As explained earlier, the GIS-based modelling for the NWSAS requires the combination of several geospatial datasets that can be divided into three groups. The first group is administrative maps showing the delineation of the NWSAS Basin, the provinces and the irrigated area. The second group relates to climatic datasets such as temperature, wind speed, solar irradiance and precipitation that were collected for each month for the period 1970-2000. The third group relates to biophysical characteristics such as elevation and water table depth that are collected on an aggregated – annual – basis.

Table 11. Summary table of the GIS layers used in the NWSAS nexus model

#	Dataset	Type	Resolution	Spatial scope	Source
1	Administrative boundaries	Vector polygon	-	Administrative levels	[228]
2	Elevation (m)	Raster	1 km × 1 km	Water/Energy demand	[229]
3	Cropland area (ha)	Raster	20 m x 20 m	Water/Energy demand	[230]
4	Irrigated harvested area (ha)	Raster	20 m x 20 m		[230]
5	Minimum monthly temperature (˚C)	Raster	1 km × 1 km	Water demand	[228]
6	Maximum monthly temperature (˚C)	Raster	1 km × 1 km	Water demand	[228]
7	Average monthly temperature (˚C)	Raster	1 km × 1 km	Water demand	[228]
8	Monthly solar radiation (kJ m^{-2} day^{-1})	Raster	1 km × 1 km	Water demand/Energy Supply	[228]
9	Monthly wind speed (m s^{-1})	Raster	1 km × 1 km	Water demand	[228]
10	Monthly precipitation (mm)	Raster	1 km × 1 km	Water demand	[228]
11	Water table depth (m)	Raster	1 km × 1 km	Energy demand	[231]

Figure 14 and Figure 15 show examples of wind speed and solar radiation maps. Table 12 and Figure 16 show the water table depth in the different provinces.

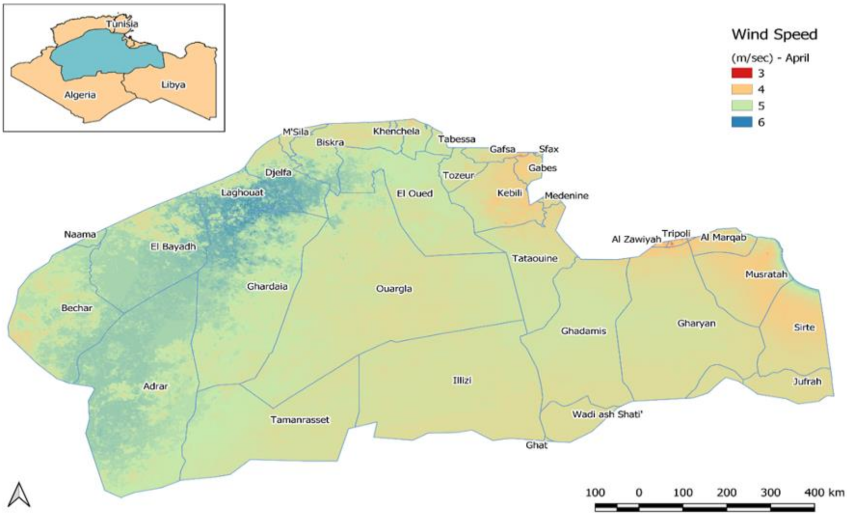

Figure 14. Wind speed in the NWSAS in (m/sec) in April.

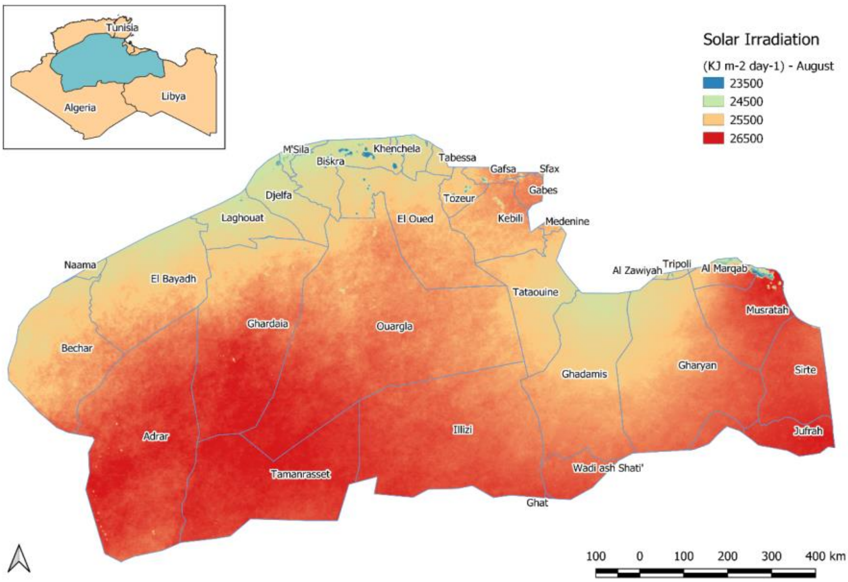

Figure 15. Solar radiation in NWSAS region (kJ m^{-2} day^{-1}) in August.

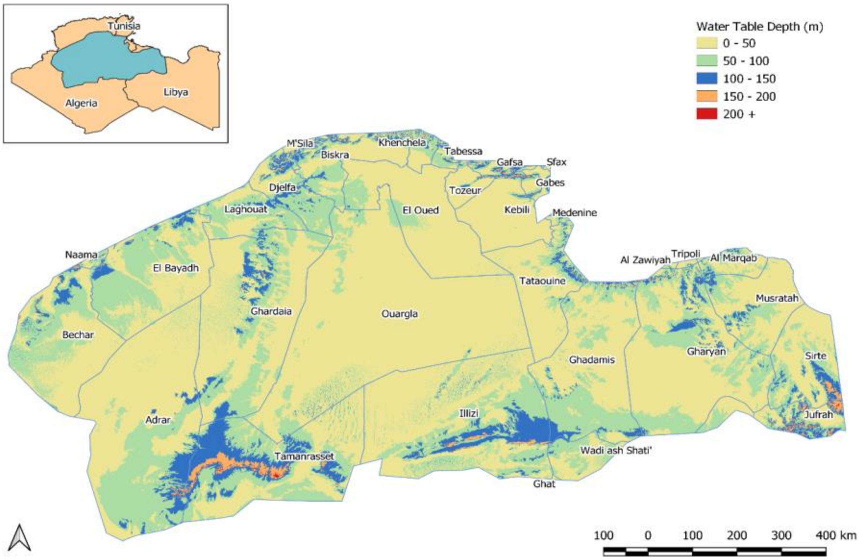

Figure 16. Water table depth in NWSAS region (m).

Table 12. Summary of water table depth values for each province.

Country	Province	Groundwater depth (m)*		
		avg	min	max
Algeria	Adrar	37	0	166
	Biskra	62	5	178
	Djelfa	44	0	180
	El Oued	35	0	81
	Ghardaia	44	0	158
	Illizi	66	0	161
	Khenchela	83	46	192
	Laghouat	12	0	77
	Ouargla	22	0	116
	Tamanrasset	72	0	226
	Tebessa	40	19	58
Libya	Ghadamis	87	0	235
	Gharyan	62	0	318
	Jufrah	57	0	252
	Musrata	27	0	130
Tunisia	Gabes	74	3	224
	Kebili	26	0	235

	Tataouine	79	0	208
	Tozeur	43	0	186

* Data extracted from the map [231].

In this analysis, different supply options are compared based on the Levelised Cost of Electricity (LCOE). This calculation maps the cheapest option available to the farmer at each location for obtaining electricity for groundwater pumping. In each of the three countries, a mix of diesel and electric pumps is used. However, the key challenge is the availability and accessibility to data showing the distribution of each technology in each country. To overcome this, it is assumed that all pumps in Algeria and Tunisia run using diesel generators and that in Libya all pumps are powered from the grid. This assumption was validated by local experts as part of the participatory process [156]. The existing options are then compared to **a)** stand-alone PV and **b)** small-scale wind turbines as shown in Table 13.

Table 13. Summary of energy supply technologies compared in each country.

#	Country	Technologies compared
1	Algeria	Diesel pumps, stand-alone PV and small-scale wind turbines.
2	Libya	Electric pumps (grid-connected), stand-alone PV and small-scale wind turbines.
3	Tunisia	Diesel pumps, stand-alone PV and small-scale wind turbines.

To understand the impact of different factors on the affordability of renewables in the region, a range of sensitivity scenarios are studied to explore the impact of two factors on the LCOE calculation at each location of the NWSAS:

a) Capital cost (CAPEX) of renewable solutions. In this case, two renewable technologies are considered: stand-alone solar PV and small-scale wind turbines.

b) Fossil fuel subsidy level: the subsidy level varies between countries and from one energy source to another. In this case, the diesel price is used for Algeria and Tunisia and the electricity price for Libya.

The changes are introduced in three phases or levels with a total of 9 scenarios. Level 1 represents the current technology costs and subsidy levels in each country. Level 2 is an intermediate change by 2030 and level 3 shows a high change by 2030. For renewables CAPEX, a drop in solar PV[9] and wind costs of 15% and 30% is assumed to represent levels 2 and 3, respectively. This change mainly reflects the learning curve for each technology. For fossil fuel subsidies, a step increase in the price is assumed at 25% and 50% for both diesel and electricity for sensitivity levels 2 and 3, respectively, as shown in Table 14. This reflects subsidy removal from these energy sources. In this case, the LCOE represents the farmers' perspective, i.e. the least cost option for powering groundwater pumping in each location.

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[9] According to the IEA WEO2018, solar PV cost in the Middle East is expected to drop 44% by 2030 compare to 2017 cost under the new policy scenario and by 54% by 2030 under the SDS scenario [232].

Table 14. Summary of the sensitivity scenarios inputs.

Techs	Parameter	Units	Levels			Sources
			1	2	3	
Diesel Gensets	Capital Cost (CAPEX)	USD/kW	938	938	938	[233] [234]
	O & M	USD/kWh	0.1	0.1	0.1	
	Life Time	Years	10	10	10	
	Fuel Cost (Diesel, Algeria)	USD/Litre	0.17	0.21	0.26	
	Fuel Cost (Diesel, Tunisia)	USD/Litre	0.62	0.78	0.93	
Electric Pump	Capital Cost (CAPEX)	USD/kW	845	845	845	[233] [235]
	O & M	USD/kWh	0.1	0.1	0.1	
	Life Time	Years	10	10	10	
	Fuel cost (Electricity, Libya)	USD/kWh	0.168	0.21	0.25 2	
Wind	Capital Cost (CAPEX)	USD/kW	1,300	1,105	910	[236]
	O & M	USD/kWh	0.02	0.02	0.02	
	Life Time	Years	20	20	20	
PV	Capital Cost (CAPEX)	USD/kW	1,140	970	680	[237] [238]
	O & M	USD/kWh	0.01	0.01	0.01	
	Life Time	Years	15	15	15	

2.3.4 The Souss-Massa Basin

The last case application, the Souss-Massa Basin in Morocco, maintains the main thread of shared water management but shifts the scale from transboundary basins to the local or sub-national basin. Paper IV aims to address research questions 3 and 4.

As demonstrated in sub-section 2.1.2, this study introduces an enhanced participatory approach and applies it to the stakeholders of the Souss-Massa Basin. The pool of stakeholders encompassed experts from water, agriculture, energy and the environment, representing different backgrounds (government agencies, academia, private sector and NGOs). Furthermore, it involved international organisations, such as The United Nations Food and Agriculture Organisation (FAO), the United Nations Development Programme (UNDP) and the Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH (GIZ), to name a few. The author, along with other experts, led the design and implementation of the new participatory approach. This was used as a showcase to build the WEF nexus capacity in the NENA region through a series of webinars.

In the quantitative part of this analysis, an integrated energy-water-agriculture nexus model is developed. This model soft-links two modelling frameworks, a GIS-based energy model and WEAP as a water balance model. Six key scenarios are studied to explore the role of different sectors in sustaining groundwater sources:

1. **Reference Scenario (REF):** Represents the current status in Souss-Massa. It assumes that the domestic demands increase over time with a population growing at 1.4% per year while the total irrigated area remains constant at 125,482 ha. This scenario can be seen as a “no measure” scenario.
2. **Desalination Scenario (DES):** This scenario represents a contribution or a measure from the water sector. It assumes that the new Chtouka desalination plant [239], [240] starts operation at a capacity of 275,000 m^3 per day in phase 1 by 2021. About 150,000 m^3 per day of desalinated water is allocated for domestic use in Agadir and 125,000 m^3 per day

for irrigating the agricultural perimeters in Chtouka. In the second phase (2030) the desalination capacity is expanded to 450,000 m^3 per day with an equal share between both consumers.

3. **Wastewater reuse scenario (WWR):** This scenario is another water-centred scenario. It assumes a combination of seawater desalination and wastewater reuse for irrigation purposes.
4. **Increased Water productivity scenario (IWP):** This scenario represents measures from the agricultural sector. Its goal is to mitigate irrigation demand by increasing water productivity. This means advances in irrigation, fertiliser application, soil tillage, and farming practices to avoid the overuse of water.
5. **Integrated Strategies scenario (INS):** This scenario is a cooperation scenario that combines different strategies from different sectors. It assumes increasing water supply through desalination and wastewater reuse while at the same time, it assumes increasing water productivity.

The impact and the robustness of these scenarios are examined based on four metrics of performance: **a)** the impact on groundwater level, **b)** the impact on unmet water demand, **c)** crop production and **d)** energy demand.

Additionally, a new module is developed in the energy part of the model. This addition is in response to the request, given to the author during the consultation process, from the Regional Directorate of Energy and Mines in Souss-Massa to explore different decarbonisation strategies related to the phasing-out of butane use in groundwater pumping. The decarbonisation module explores 12 scenarios that are based on two decision criteria. The first is the last year for butane use (phase-out year), and the second is the level of PV adoption in the basin. The following table gives an overview of the scenarios:

Table 15. summary of the scenarios developed for the decarbonisation of the agricultural sector in the Souss-Massa Basin

1) Butane phase-out year:		
1.1 None (till 2050):	**1.2 Late phase-out (by 2040):**	**1.3 Early phase-out (by 2030)**
The use of butane will continue up to the end of the modelling period (2050) at the same share of 20% of the irrigated area.	The use of butane will gradually decrease until it is completely phased out by 2040.	The use of butane will gradually decrease until it is completely phased out by 2030.

2) PV adoption level (in the total electricity demand for groundwater pumping):			
2.1 at 10%	**2.2 at 20%**	**2.3 at 40%**	**2.4 at 60%**
The current share of PV will continue up to the end of the modelling period (2050).	Aims at reaching a 20% share of PV by 2040.	Aims at reaching a 40% share of PV by 2040.	Aims at reaching a 60% share of PV by 2040.

The comparison between the different supply technologies is based on the techno-economic characteristics of each technology. Table 16 lists the key inputs used in this part of the analysis:

Table 16. Key inputs and assumptions used in the energy calculations and butane phase-out scenarios

#	Parameter	Value	Unit	Source
1	Cost of electricity production from Coal	0.65	MAD/kWh	Consultation with local experts [176]
2	Cost of electricity production from CSP	1.4	MAD/kWh	Consultation with local experts [176]
3	Cost of electricity production from PV	0.44	MAD/kWh	Consultation with local experts [176]
4	Avg Cost of electricity production from the national grid	0.57	MAD/kWh	Computed based on technology shares and costs.
5	PV capital cost	7,000	MAD/kW	Consultation with local experts [176]
6	PV O&M Cost	1	% of the capital cost	Assumption
7	Butane subsidy	80	MAD/bottle (12kg) of Butane	Consultation with the Regional Directorate of Energy and Mines in Souss-Massa. [176]
8	Butane consumption in agriculture in Souss Massa (2019)	84,000	tons/year	
9	Butane use in Agriculture compare to total use of butane	36	%	
10	Share if Agricultural sector emissions (2016/2017)	5.4	% of total emissions	[178]
11	Emissions from electricity and heat producers	23	Mt of CO2	[178]
12	Total emissions in Morocco (2017)	58	Mt of CO2	[178]
13	The emission factor of electricity from the grid	0.7	kgCO2/kWh	Computed based on data from [241]
14	Butane emission factor	3.1	kgCO2/kWh	Computed based on data from [242]
15	Electric pump efficiency	45	%	Consultation with local experts [176]
16	Butane-driven pump efficiency	20	%	Consultation with local experts [176]

3 Results and discussion

This chapter presents the main research findings. The chapter is divided into four sections. Section 3.1 refers to the first research question on the role of the energy sector in motivating cooperation in transboundary water management. Section 3.2 refers to the second research question on the implications of climate change on the security of electricity supply in shared water basins and the role of renewable energy. Section 3.3 focuses on the benefits of considering the integrated energy-water-agriculture nexus in shared groundwater management. Finally, section 3.4 focuses on the integrated energy-water-agriculture nexus and the shift to low-carbon agriculture. Each section presents selected results from more than one paper that are the most relevant to addressing each research question.

3.1 The role of the energy sector in motivating cooperation in transboundary water management.

In this section, insights from the energy-water models of the Drina and the Drin River Basins are presented. Both studies apply, within the electricity supply model, a hydrological representation of the river system and the cascade of hydropower plants in each basin. Such a model setup allows exploration of the impact of the cooperation measures on the electricity generation from the hydropower plants in the basin as well as total generation from the electricity supply infrastructure in the riparian states. In other words, the model structure makes it possible to quantify how the energy sector could motivate transboundary cooperation in shared water basins.

3.1.1 Cooperation to increase electricity supply (benefits at the national scale)

Two scenarios are compared in the analysis, the reference no-cooperation (or BASE) scenario versus a cooperation (COP) scenario (paper I). The no-cooperation scenario simulates a minimum outflow from the Piva hydropower plant (upstream) for one month of the year, which simulated an extreme historic operation and for the rest of the year the model is allowed to optimise the outflow from Piva. In contrast, in the cooperation scenario, the outflow from Piva (and other upstream plants) is optimised to maximise the benefit for all hydropower plants in the basin based on a least-cost objective. This means that the model optimises the electricity generation mix for the three countries (including the HPPs in the Drina Basin) to meet the final demand for electricity at the lowest system cost for the three countries. The model decides how much electricity should be generated from Piva and other HPPs in the basin, how much water should be released, and how much should be stored in the dams in each time slice.

The analysis shows that while the annual generation from Piva remains unchanged, an approximately 3% (annual average) increase in electricity generation can be achieved from the downstream power plants under cooperation conditions. This is owing to an optimised flow regime in the basin that ensures timely water availability downstream by altering the water release (and operation) from the upstream HPPs, especially Piva. The generation from the Bajina Bašta hydropower plants (in Serbia) increases by a total of 520 GWh for the period 2017-2030 relative to the baseline. Visegrad hydropower plant (in Bosnia and Herzegovina) produces an additional 390 GWh of electricity and Zvornik (also in Bosnia and Herzegovina but further downstream) produces an additional 113 GWh during the same period as shown in Figure 17. The differences in generation gains can be attributed to the different installed capacities of the hydropower plants (see Table 3) and their relative location in the cascade.

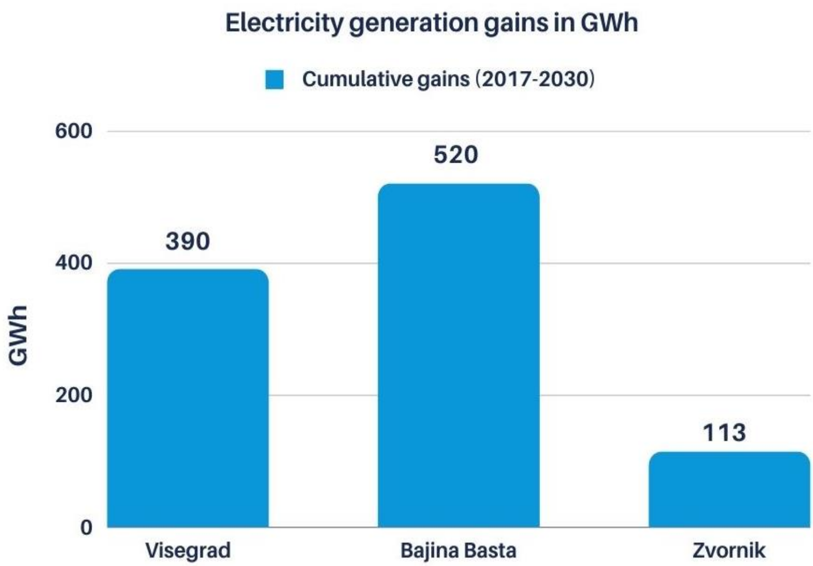


Figure 17. Electricity generation gains between the COP scenario and the BASE scenario for the hydropower plants downstream of Piva for the period 2017-2030.

In a similar independent research study on the Volta River Basin, Gonzalez et.al [70] explore the potential impacts the Pwalugu Multipurpose Dam (PMD) could have on the existing infrastructure and water services of the Volta River Basin (in west Africa shared between Benin, Burkina Faso, Côte d'Ivoire, Ghana, Mali, and Togo). Two alternative scenarios assuming cooperation and non-cooperation are used to explore the impact of upstream HPP (in Burkina Faso) on the PMD (in Ghana). The study concludes that the cooperative scenario results in net positive energy production in the downstream country (Ghana). Which confirms the findings of this dissertation.

3.1.2 Cooperation to increase electricity trade (benefits at the international level)

This section explores another dimension in which the energy sector can motivate transboundary cooperation. In the electricity trade scenario (COP_TRD) (paper I), the impact of cooperation in maximising the benefits of electricity trading is explored. The interconnectors between the three riparian states of the Drina Basin and the riparian states and other countries were modelled.

Contrary to the base scenario, where electricity trade was limited to the historical maximum values (Table 8) for the period between 2008 and 2014, in the (COP_TRD) scenario this constraint is relaxed. The model is allowed to increase the trade limits gradually from 2022 until 2025 by up to 40%. This percentage is an assumption based on consultation with stakeholders [243] and on comparing the annual variation of electricity trade between 2008 and 2014 [209].

As shown in Figure 18, under the conditions of this scenario, the three countries increase the amount of electricity traded once the constraints are relaxed. This is due to the low-cost surplus electricity being generated mainly from hydropower and coal. Bosnia and Herzegovina (Figure 18 – a) continues to be a net exporter to Montenegro and Croatia. Serbia also demonstrates a similar trend of increasing electricity export over the coming decade (Figure 18 – c). Both hydropower and coal play an important role in this trend. Therefore, the decommissioning of the 1,135 MW "Kostolac" coal power plant that was installed in the late 1960s causes a drop in Serbian exports by 2027. In the case of Montenegro, the introduction of the high-voltage undersea cable connection to Italy (also modelled in this scenario) plays an important role in unlocking trade potential. The 1 GW and 415 km long interconnector increases the flow of electricity from Montenegro to Italy and at the same time increases the flow from other neighbouring countries into Montenegro (as shown in Figure 18 – b) which acts as a transit station. It can be argued that cooperation between the riparian states in maximising hydro generation and the development of the electricity trade market will have a positive impact on the regional trade among the countries and with neighbouring countries in the region. This insight is in line with the Trans-Balkan corridor project [244] and the National Renewable Energy Action Plan of Montenegro [245].

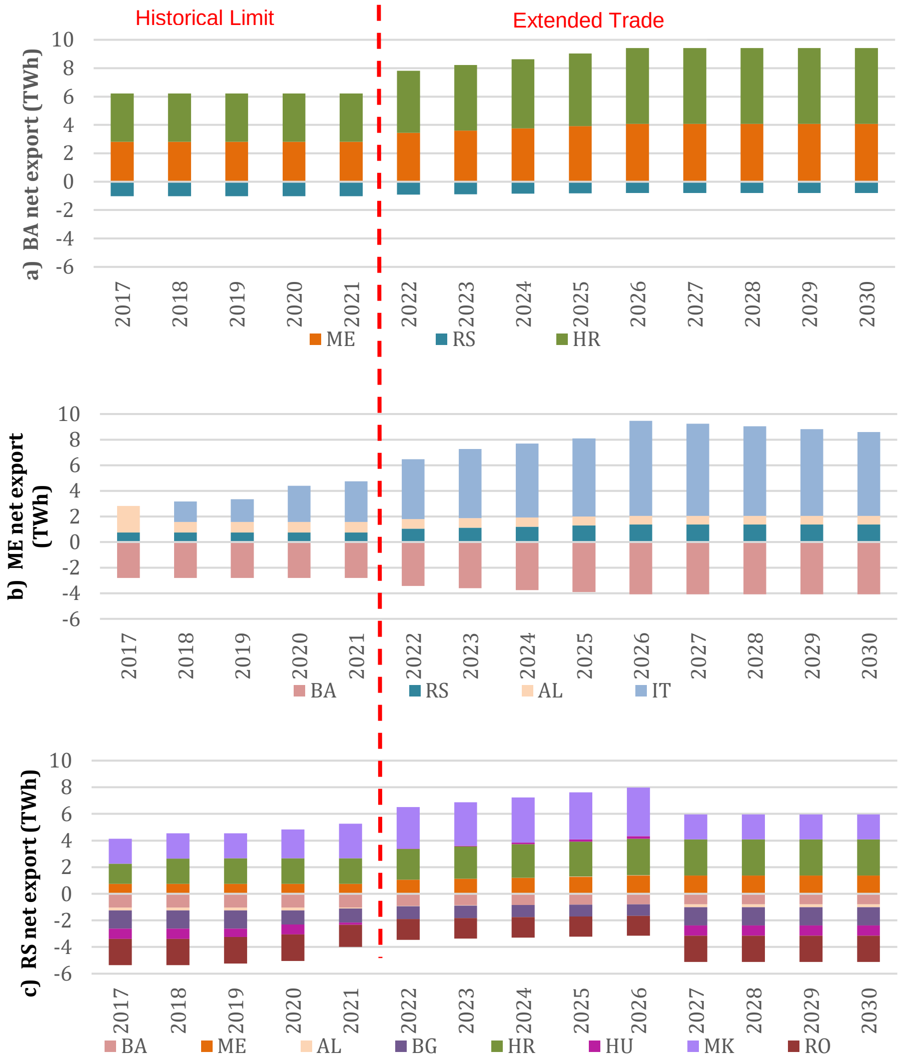


Figure 18. Trade profile for the three countries in the Drina Basin under the cooperative extended trade scenario (COP_TRD).

Positive values indicate experts and negative values indicate imports. [AL: Albania; BA: Bosnia and Herzegovina; BG: Bulgaria; HR: Croatia, HU: Hungary; IT: Italy; ME: Montenegro; MK: Macedonia; RO: Romania; RS: Republic of Serbia]

3.1.3 Cooperation to mitigate the risk of extreme climate events.

The contribution of the energy sector to mitigating the risk of floods is explored in this dissertation through the implementation of new operational rules for the Spilje and Fierza hydropower plants in the Drin Basin (paper II). The impact of the new operational rules is then quantified in terms of **a)** additional storage capacity (buffer volume, in MCM) to be used during floods, and **b)** the change in electricity generation (in GWh) from the hydropower plants subject to a change in buffer volume. Three scenarios are compared in this section. A reference (**REF**) scenario with the current operational rules. Flood Protection with 5% additional buffer volume (**FP05**), and Flood Protection with 20% additional buffer volume (**FP20**).

The additional storage volume was calculated using the Area-Volume-Elevation (AVE) curves of the reservoirs [40], taking into account the minimum and maximum operation levels of each reservoir. In Spilje reservoir, which has a relatively smaller storage capacity compared to Fierza, increasing the buffer volume by 5% (FP05) results in reserving an additional 7 - 9 MCM of buffer volume and reducing the water head by 2 - 2.9 m, while the 20% increase (FP20) translates into a 26 - 34 MCM additional buffer and a reduction of the water head by 3.8 - 4.3 m as shown in Figure 19 and Table 17. The changes in the water head are then introduced to OSeMOSYS to estimate the changes in electricity generation.

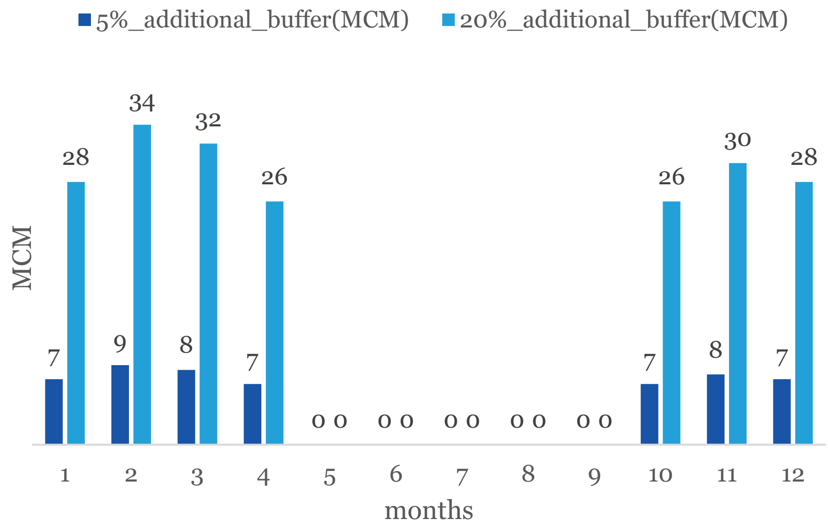


Figure 19. Additional buffer volume gained (MCM) by increasing the buffer volume of the Spilje dam by 5% and 20%, respectively.

[Note: The water level and the volume of water stored in each dam change each month based on water availability and the operational rules as shown in tables 13 and 14. This is why the additional 5% and 20% can not be introduced as a constant volume but rather it varies each month.]

In this case, the trade-off is a lowering of the water level in the Spilje dam (i.e., the head) by 2 - 4.3 m as shown in the following table.

Table 17. Changes in the operational rules and the water level (m.a.s.l) in Spilje dam.

Month	Hist level (REF)	New Level (FP05)	New Level (FP20)	Diff (FP05-REF)	Diff (FP20-REF)
1	569	566.3	564.7	2.7	4.3
2	566	564	562.2	2	3.8
3	567	564.7	563	2.3	4
4	570	567.1	565.7	2.9	4.3
5	576	576	576	0	0
6	578	578	578	0	0
7	576	576	576	0	0

8	575	575	575	0	0
9	572	572	572	0	0
10	570	567.1	565.7	2.9	4.3
11	568	565.5	563.9	2.5	4.1
12	569	566.3	564.7	2.7	4.3

In the case of the Fierza reservoir, increasing the buffer volume by 5% (FP05) translates into 36 – 68 MCM of additional flood storage capacity while adding a 20% (FP20) buffer translates into 144 - 270 MCM of additional storage capacity to be used for flood mitigation (Figure 20). The large overall storage capacity in the Fierza reservoir (compared to Spilje), makes the gains in terms of additional flood storage capacity more significant for Fierza.

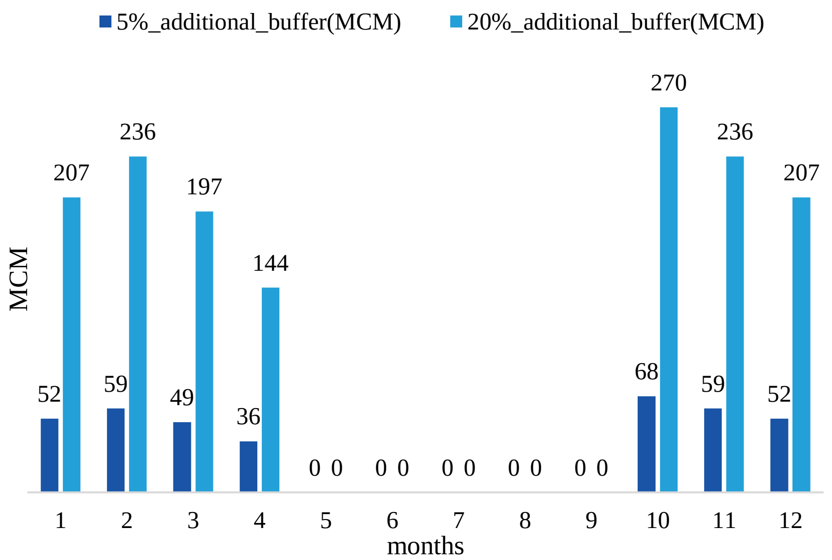


Figure 20. Additional buffer volume gained (MCM) by increasing the buffer volume of the Fierza dam by 5% and 20%, respectively

Similarly, increasing the buffer volume results in a lowering of the water level in the Fierza dam by between 0.5 – 7.8 m as shown in the table below.

Table 18. Changes in the operational rules and water level (m.a.s.l) in Fierza dam.

month	Hist level (REF)	New Level (FP05)	New Level (FP20)	Diff (FP05-REF)	Diff (FP20-REF)
1	279	278.5	275	0.5	4.2
2	276	274.9	270	1.1	5.8
3	280	279.7	276	0.3	3.8
4	285	285.3	283	-0.3	1.7
5	290	290	290	0	0
6	296	296	296	0	0
7	293	293	293	0	0
8	286	286	286	0	0
9	275	275	275	0	0
10	272	270.1	264	1.9	7.8
11	276	274.9	270	1.1	5.8
12	279	278.5	275	0.5	4.2

The changes in the operational rules are implemented as inputs to the dam storage characteristics in OSeMOSYS. This alters the electricity generation based on the new storage capacity and the available water in the reservoirs. The model results show that increasing the buffer volume has only a small impact on electricity generation when compared to the savings in flood damages. The average generation losses range from 7 - 10 GWh per year (2.2 – 3.2%) in Spilje to about 5 – 28 GWh per year (0.3 - 1.5%) in Fierza as shown in Figure 21–a and Figure 21-b. This represents a fiscal deficit of EUR 560 – 800 k in North Macedonia and between EUR 400 – 2,240 k in Albania for the FP05 and FP20 scenarios respectively (see Table 19). These values are much lower than flood damages. As mentioned in section 1.4.2, the estimated costs of damages from the December 2010 flood exceeded EUR 40 million in Montenegro alone [145].

Table 19. Summary of the changes in electricity generation in the Spilje and Fierza hydropower plants.

	Spilje HPP		Fierza HPP	
Parameter	**FP05**	**FP20**	**FP05**	**FP20**
% decrease in annual generation	- 2.2 %	- 3.2 %	- 0.3 %	- 1.5 %
Mean annual decrease in generation (GWh)	- 7	- 10	- 5	- 28
Losses in monetary values (EUR)*	-560,000	-800,000	-400,000	-2,240,000
*Based on average household electricity prices in each country (2013-2019) [246]				

Looking at the total electricity supply from all of the hydropower plants in the Drin Basin, it can be seen that the decrease in supply is almost negligible (Figure 21–c). This is attributed to the fact that the generation from other hydropower plants in the basin increases and thus compensates for the drop in Spilje and Fierza. Since less storage (for electricity generation) is available in Spilje and Fierza, the model directs the extra available water in the cascade to other dams which results in them increasing their generation. It is important to note that the generation from the other hydropower plants (Globocica, Koman and Vau I Dejes) varies depending on turbine capacity, storage capacity, water availability and other parameters.

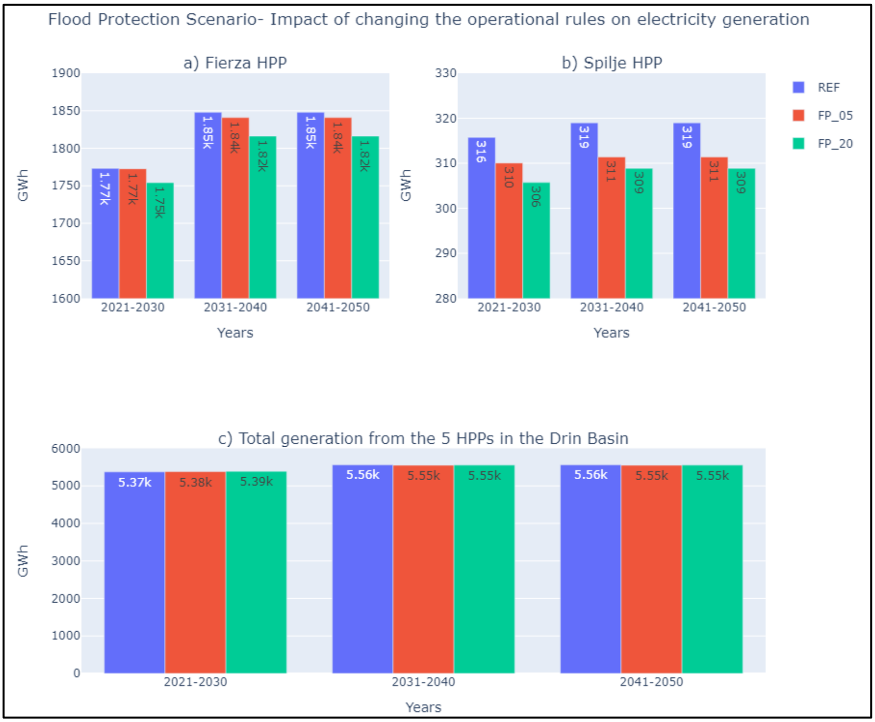


Figure 21. Change in electricity generation under the flood control scenario. A) Impact on Fierza HPP in Albania, **b)** Impact on Spilje HPP in North Macedonia and **C)** Total generation from the five HPPs in the Drin Basin from both Albania and North Macedonia.

These indicative results show that the energy sector can play an important role in mitigating the risk of extreme climate conditions. As shown above, rethinking the operational rules of hydropower plants to reserve additional volumes for better flood management may not jeopardise the security of electricity supply but is expected to provide important storage volumes that could save many lives during flood events.

In complementary studies, researchers have used the outcomes of the Drin OSeMOSYS model to estimate the changes in the flooded area and flood damage in Albania and Montenegro. The estimates (based on several modelling tools) show that the 20% increase in buffer volume has the potential to reduce the flooding damage by about 30% in Montenegro and about 60% in Albania which is equivalent to savings of EUR 0.3 million for Montenegro and EUR 17.5 million for Albania [132].

3.2 What risks and opportunities emerge from the interplay between climate and renewable energy in shared basins?

This section also relates to the Drin River Basin (paper II) and draws insights from the energy-water model. Sub-section 3.2.1 focuses on the implications of climate change on the security of electricity supply. Sub-section 3.2.2 focuses on the role of variable renewable energy (VRE) sources in mitigating the risk of climate change.

3.2.1 Implications of climate change on the security of electricity supply

This dissertation explores three climate scenarios and compares them to a baseline or reference scenario. The latter assumes historical climate patterns repeat over the modelling period. The climate change scenarios assume the river flows projected under RCPs 2.6, 4.5 and 8.5 (see section 2.3.2 and the GitHub repository [247]). The impact is quantified in terms of change in electricity generation from the hydropower plants in the Drin Basin (paper II).

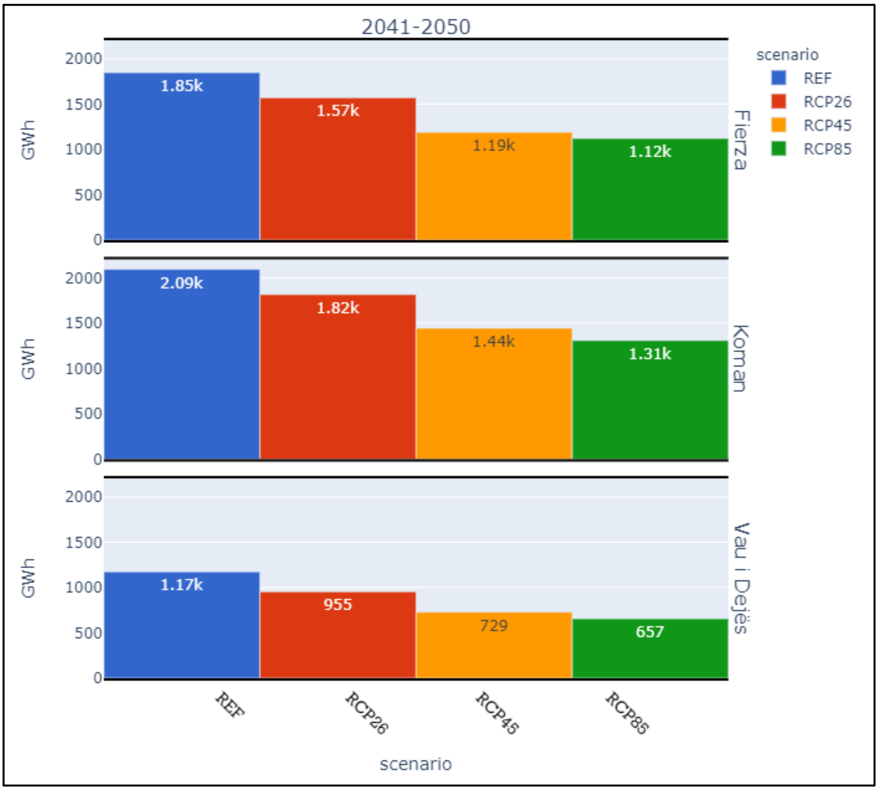


Figure 22. Average annual electricity generation from the hydropower plants in the Albanian cascade under different scenarios (REF, RCP2.6, RCP4.5 and RCP8.5).

Figure 22 shows the average annual electricity generation (GWh) for the period 2041-2050 from the three hydropower plants in the Albanian part of the Drin Basin, namely: Fierza, Koman and Vau i Dejës. These results are based on cost minimisation under the reference and climate change scenario constraints. It can be seen that the three climate projections (RCP2.6, 4.5 and 8.5) show a consistent decline in precipitation which results in decreased river flow in the Drin tributaries and decreased electricity generation. Another observation is that the impact of climate change varies slightly between hydropower plants. Fierza, which is the first reservoir and power plant of the Drin cascade, has less water available due to climate change and suffers from a reduction in electricity generation of 15%, 36% or 40% under RCPs 2.6, 4.5 and 8.5, respectively when compared to the reference scenario. The next hydropower plant in the cascade, Koman has a similar drop in production of 13%, 31% or 37%, respectively. However, Vau i Dejës, which comes last in the cascade, experiences higher declines of 19%, 38% and 44%, respectively, under the same climate conditions.

Translating the percentages into absolute values shows different orders of impact. Taking for example the RCP8.5 scenario, the Koman hydropower plant loses an average of 785 GWh per year, while the Fierza hydropower plant loses 726 GWh and Vau i Dejës 518 GWh. These differences result from the differences in installed capacity in each hydropower plant (see Table 4).

From the national perspective, as shown in Table 20 climate change scenarios show that the Albanian grid suffers a deficit of supply from the Drin Basin of 775 GWh,1,754 GWh or 2,028 GWh annually under RCPs 2.6, 4.5 and 8.5, respectively.

Table 20. Summary of the average electricity generation in each of the HPPs in GWh under the climate change scenarios – average generation in 2041-2050

Country		N. Macedonia			Albania			
Scenario/ HPP		Globocica	Spilje	Total	Fierza	Koman	Vau i Dejës	Total
Generation (GWh) - REF scenario		127	319	446	1,848	2,094	1,174	5,117
RCP26	Generation (GWh)	62	281	343	1,571	1,816	955	4,342
	Diff. compare to REF (GWh)	-65	-38	-103	-277	-278	-220	-775
	% Difference	-51	-12	-23	-15	-13	-19	-15
RCP45	Generation (GWh)	56	236	292	1,189	1,445	729	3,363
	Diff. compare to REF (GWh)	-71	-83	-154	-658	-650	-446	-1754
	% Difference	-56	-26	-35	-36	-31	-38	-34
RCP85	Generation (GWh)	53	162	215	1,122	1,309	657	3,088
	Diff. compare to REF (GWh)	-74	-157	-231	-726	-785	-518	-2,028
	% Difference	-58	-49	-52	-39	-37	-44	-40

Similarly, the impact of climate change on the electricity generation from the hydropower plants in North Macedonia has a similar trend across the RCPs. North Macedonia has two hydropower plants (Globocica and Spilje) which are upstream relative to the Albanian hydropower plants. However, they have smaller storage reservoirs and less electricity generation capacity.

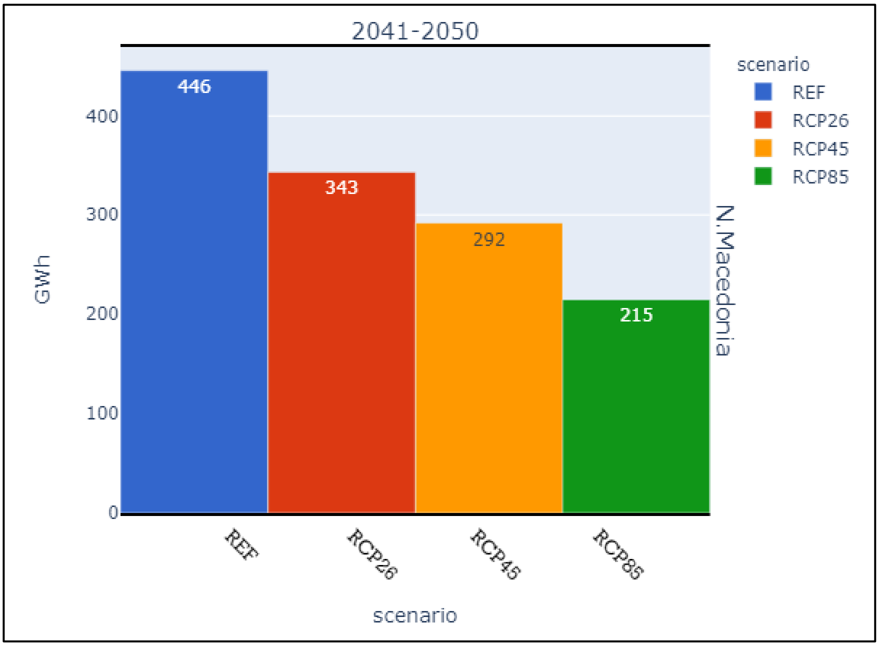
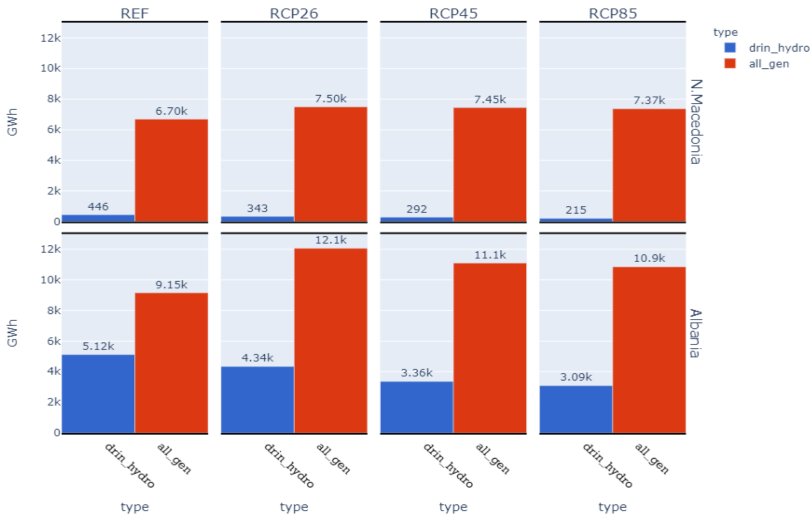
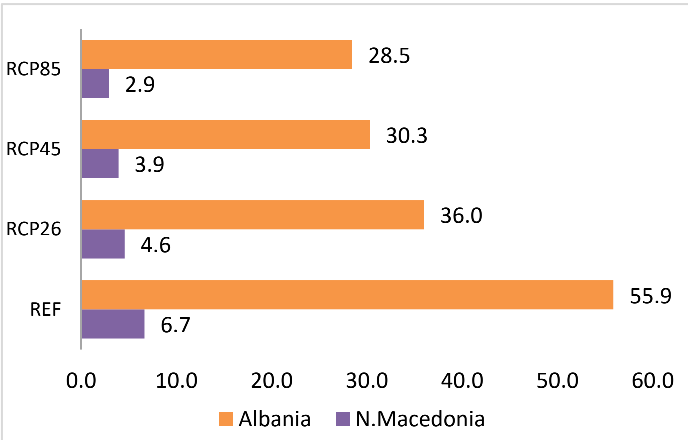


Figure 23. Total change in electricity generation from Globocica and Spilje hydropower plants (combined) in North Macedonia.

The annual decline in electricity generation from Globocica hydropower plant has values of 65, 71 and 74 GWh, while the equivalent values for the decline in generation from Spilje hydropower plant are 38, 83 and 157 GWh, each series of values corresponding to RCP2.6, RCP4.5 and RCP8.5, respectively. On a national scale, about 100-230 GWh less electricity is supplied annually to the North Macedonian grid in the last decade from 2041-2050. This translates into a reduction of 23-52% in electricity generation compared to the reference scenario (Figure 23).



a) Absolute generation in (GWh)



b) Hydropower generation as a fraction of total domestic generation (%)

Figure 24. Vulnerability of the power system to climate change.

Comparison of electricity generation from the Drin Basin hydropower plants to the total domestic generation for Albania and North Macedonia. a) in absolute values (GWh) and b) fraction (%) of generation.

Comparing the contribution of the Drin Basin hydropower plants to total domestic generation, as shown in Figure 24, it can be seen that the vulnerability of the Albanian power system to climate change is higher than that of North Macedonian. In Albania, the share of Drin hydropower to the total domestic generation drops from about 56% in the reference scenario to about 28% under the RCP8.5 scenario, while in the case of North Macedonia, the contribution of the Drin Basin hydropower declines from 7% to 3% of total domestic generation under the same scenarios.

Under the conditions assumed in this dissertation, the decline in hydropower generation due to climate change is compensated mainly by non-hydro renewables. This means that the security of electricity supply is maintained and even improved if the investments in other renewables are ensured as elaborated in section 3.2.2.

However, before that, it is worth highlighting that in this dissertation the hydrological outputs (i.e. run-off data for the Drin river and its tributaries) for each RCP are based on an ensemble of different GCMs and RCMs (see Table 10). This approach is followed to alleviate uncertainty and define robust signals for future projections [230]. An alternative approach would be to model a large number of scenarios to cover all possible climate projections and introduce a range of plausible climate impacts. As suggested by [248], multiple plausible futures should be considered in planning decisions to ensure the robust performance of long-term infrastructure under different climate conditions.

3.2.2 The role of VRE in mitigating climate change impact.

This section explores what role variable renewable energy technologies could play in mitigating the impact of climate change. The insights for this question will be drawn from the Drin Basin case (paper II).

In this dissertation, all the planned renewable energy projects (solar, wind and hydro) in Albania, North Macedonia, Montenegro and Kosovo are considered. Additionally, under the climate change scenarios (discussed in section 3.2.1), the constraints on solar and wind technologies are relaxed. This means allowing the model to increase investment in solar and wind beyond the limits of the currently announced projects provided the new additions are cost-competitive. Of course, renewable generation is constrained by the limits of the technically exploitable potential in each country. This addresses the question of whether the planned projects are enough to mitigate the risk of climate change or if additional investments are needed.

It is observed that solar and wind capacities in Albania triple under the climate change scenarios (compared to the reference scenario) to overcome the decline in hydropower. Investments in solar capacity reach 2,250 MW under climate change scenarios compared to only 660 MW in the reference scenario and investments in wind technology reach 970 MW compared to 330 MW as shown in Figure 25–a. In terms of generation, in the last modelling decade (2041-2050), solar generation increases from 914 GWh in the reference case to above 3,000 GWh under the climate change scenarios. Wind increases from about 500 GWh to 1,500 GWh under the same conditions as shown in Figure 25–b.

In North Macedonia, the energy market penetration of solar and wind is relatively lower. Investments in solar reach 2,280 MW under climate change scenarios compared to 1,600 MW in the reference case, while wind has almost the same capacity of 640 MW in all scenarios. In terms of generation, in the last decade (2041-2050), solar generation in North Macedonia increases from about 2,200 GWh to 3,000 GWh and wind generation remains at the same level of 735 GWh.

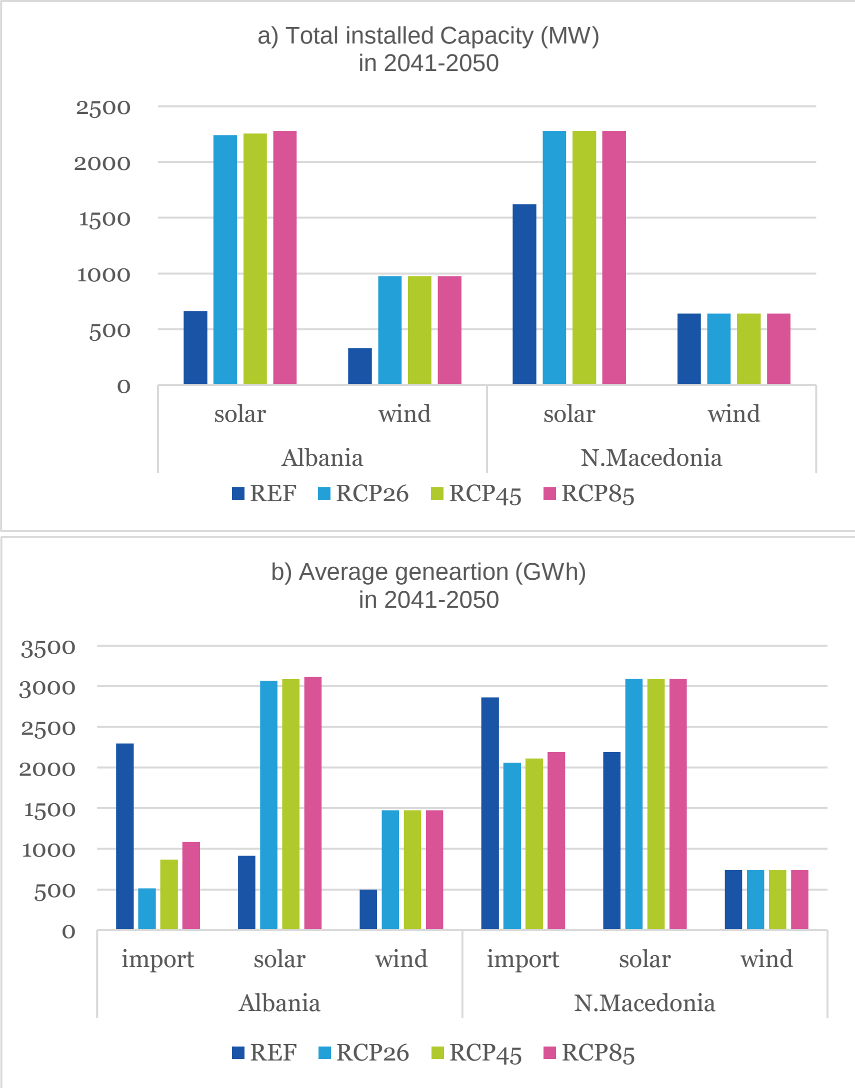


Figure 25. Solar and wind power in Albania and North Macedonia,
a) Total installed capacity (MW) in the period 2041-2050, b) Average generation (GWh) in the same period.

The difference between solar and wind investment arises for two reasons. The first reason is the relatively lower investment cost of solar projects compared to wind projects. The costs assumed in this dissertation are based on the announced projects in each country as shown in Table 9.

The second reason is the difference in solar and wind potentials in each country. As shown in Figure 26 in Albania and North Macedonia wind power has a relatively lower capacity factor than solar power. It is worth highlighting that the capacity factors of solar and wind are spatially distributed between inside and outside the basin and temporally distributed among the weekly time slices of the model. Figure 26 shows the aggregated average value per type of power technology in each country for ease of representation.

It should be noted that increasing the share of VREs such as solar and wind may require an increase in the system flexibility and maintaining a balance between supply and demand [249] [250]. However, the Drin model structure and the insights drawn from the analysis do not address this aspect because the purpose of the analysis is the long-term impact of climate change. Hence the weekly averages used for both the final electricity demand and the VRE capacity factor are deemed suitable for the long-term scope of this study. Additionally, the level of complexity and temporal resolution is kept at this level for capacity-building purposes. The short-term analysis or the system flexibility question can be explored either by using a short-term modelling tool such as electricity market and dispatch models (e.g. PLEXOS [251]) or by incorporating flexibility requirements into OSeMOSYS code as studied by Welsch et al.[252].

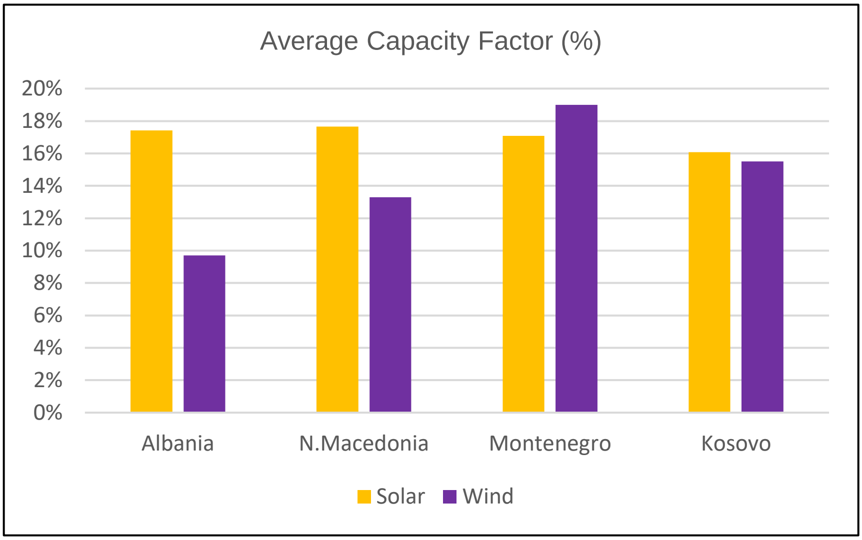


Figure 26. The average capacity factor for solar and wind power in each country [217], [218].

3.3 What benefits can the consideration of the energy-water-agriculture nexus bring to shared groundwater management?

This section draws insights from the integrated energy-water-agriculture nexus assessments in the North Western Sahara Aquifer System (paper III) and the Souss-Massa Basin (paper IV). The assessments aim to address a number of shared management questions related to irrigation requirements (sub-section 3.3.1); the energy implications of groundwater pumping (sub-section 3.3.2); and the spatially explicit least-cost electricity supply options for meeting irrigation demand (sub-section 3.3.3).

3.3.1 Irrigation requirements and the impact of changing irrigation systems on water conservation

This dissertation quantifies the irrigation water requirements for selected crops in the NWSAS region and the associated pumping needs. This is done through the implementation of the energy-water-agriculture nexus approach and the development of an open-source and spatially explicit energy-water-agriculture model for the NWSAS as explained in section 2.2.32.2 and section 2.3.3.

Figure 27 shows that the NWSAS region requires an average of 11,700 m^3/ha annually or 3,250 MCM (in total) of water to satisfy its irrigation requirements. It can be seen that the provinces of Adrar, Illizi, Tamanrasset and Jufrah have the highest irrigation demand exceeding 14,000 m^3/ha. The requirement for other provinces is between 10,000 – 12,000 m^3/ha while only Musratah is below the 10,000 m^3/ha threshold. The irrigation water requirements depend, among other things, on evapotranspiration. This in turn depends on wind speed, temperature and solar radiation. Areas like Adrar have high wind speed (Figure 14) and solar irradiance (Figure 15) which results in higher evapotranspiration and accordingly higher irrigation needs. Additionally, the type of crops cultivated in each province also influences the irrigation requirements.

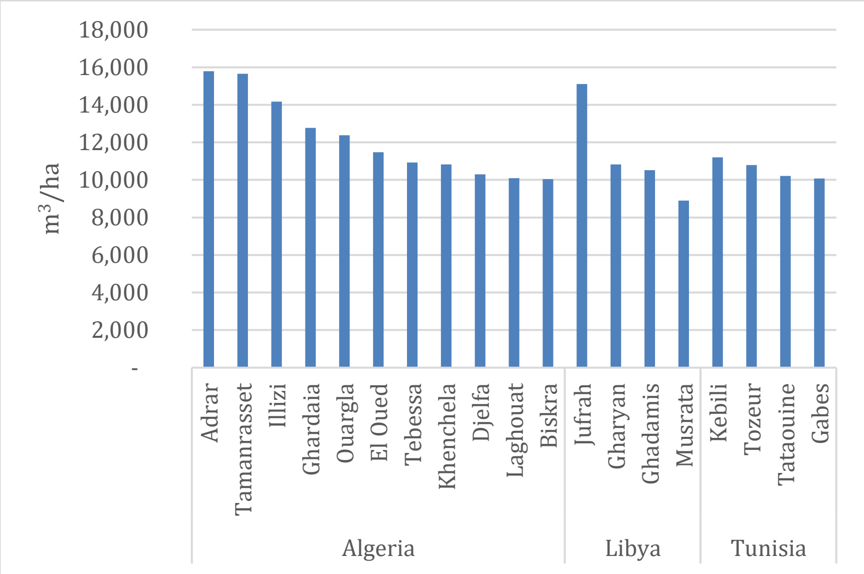


Figure 27. Estimated annual water demand level (m^3/ha) in each province based on the selected crops modelled in each province.

It is worth noting that the interaction with the stakeholders through the TBNA nexus process brings different sectors and stakeholders together to discuss the shared management challenges and work on solutions. This was reflected in developing a common understanding and agreement on the priority nexus challenges in the basin. It was also reflected in the development of the first energy-water-agriculture model that covers the entire NWSAS region. This in itself is an added value of this research. Such a model allows for scenario development and informs management decisions by providing insights at the basin level that would be difficult to achieve without such a basin-wide nexus model. One example is the impact of improving irrigation efficiency on water abstraction.

The irrigation efficiency in the NWSAS area is very low with an efficiency of just 42% averaged across the basin [129]. In a water-scarce region such as the NWSAS, having such high irrigation requirements and very low irrigation efficiency is highly detrimental to agriculture, which is the main socioeconomic activity for the people in this region. One of the strategies for reducing the high irrigation demand is to improve the irrigation system and reduce losses.

The model shows that improving the irrigation technique from surface irrigation, which is currently the dominant technique, to drip irrigation results in saving up to 1.5 BCM of water abstraction every year. About 70% of the savings come from the Algerian part due to its large share of the total area and the intensity of irrigation in the Algerian provinces as previously noted. Reducing water abstraction means reducing the energy requirement for pumping and the resulting emissions (since most of the pumping is powered by fossil fuel technologies). It should be noted that water abstraction savings due to a better irrigation system could easily be lost if the irrigated area were to be increased or if farmers shifted to more water-intensive crops. This is a typical “rebound effect” as demonstrated by water efficiency measures in the NENA region [253]. Therefore, irrigation efficiency measures should go hand in hand with other measures such as raising of awareness and installation of water monitoring systems. This underlines the importance of coordinated actions across sectors and across countries to sustain the shared water source which brings us back to the first research question of this dissertation.

3.3.2 Energy implications of groundwater management strategies

In many parts of the world where groundwater pumping is powered by decentralised systems such as diesel generators, it is difficult for policymakers to know how much energy is actually consumed by pumping. The NWSAS (paper III) is one example because a large share of pumping is powered by diesel generators and there is a lack of data on how much energy is consumed. Even in areas where electricity from the grid is used (i.e. in Libya), data is not available on the electricity actually used for irrigation purposes. As mentioned earlier (in section 1.4.3), the consideration of energy aspects is missing from previous studies on the NWSAS.

One way that the energy-water-agriculture nexus analysis can support the sustainable management of shared groundwater basins is by spatially and quantitatively estimating the electricity requirements for pumping in each location and the region in total. This can provide important insights for policymakers. For example, which locations should be prioritised for the deployment of renewables? The electricity demand depends on a number of parameters such as the efficiency of the pumps, the volumetric demand for water and the water table depth, to name a few. Such a spatially explicit analysis is a key contribution of this dissertation.

The modelling results show that the total annual electricity demand for the entire NWSAS area is about 730 GWh. The largest part of this demand is consumed by Algeria with 70%, followed by Libya with 21% and Tunisia with just 9%. Four out of nineteen provinces in the basin, namely Eloud, Adrar, Ghardaia and Ouargla (all in Algeria), consume almost 55% of the total energy for pumping in the NWSAS, because of the high volumes of water pumped in these locations (Figure 27). Musratah in Libya and Touzer in Tunisia consume the greatest amount of energy in their respective countries but this is still considerably less than the electricity consumption in the aforementioned Algerian provinces.

Improving the efficiency of the irrigation system reduces the electricity requirement for pumping. The total annual demand reduces from 730 GWh with the current surface irrigation system to 505 GWh and 385 GWh using the improved surface irrigation and drip irrigation systems, respectively.

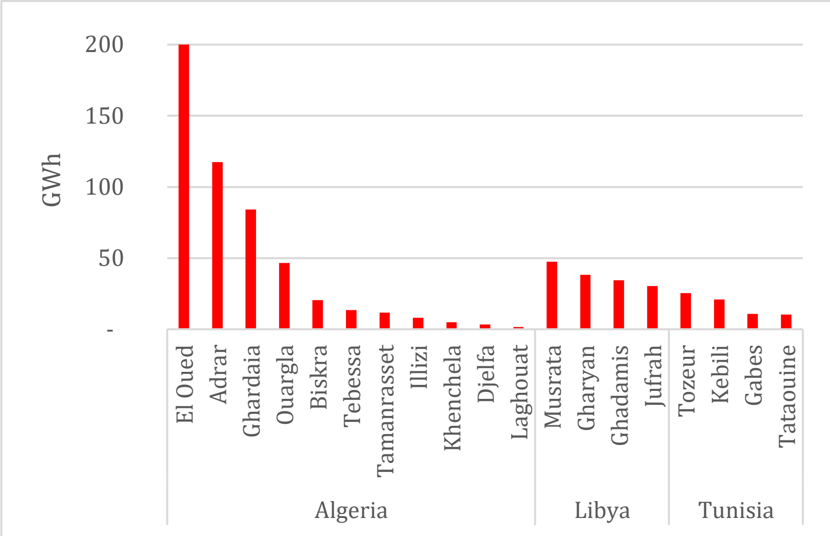


Figure 28. The estimated electricity demand (GWh) for pumping in each province.

Another interesting observation is that although the annual water abstraction in Kebeli is higher than in Touzer, the associated energy requirement is higher in Touzer. This can be attributed to the average depth of the water table level which reaches 43 m in Touzer while in Kebili is only 26 m (Table 12 and Figure 16).

The NWSAS case shows that groundwater pumping requires a considerable amount of energy. A similar insight can be gained from the Souss-Massa Basin (paper IV). In this case, six measures or scenarios are studied (see section 2.3.4) to explore the role of different strategies in sustaining water sources and improving agriculture. The impact of each strategy is evaluated based on four metrics of performance: impact on water table level, impact on unmet water demand, impact on agricultural productivity and the energy requirement of each measure. The focus of this dissertation is on energy requirements.

The integrated energy-water-agriculture model of Souss-Massa shows that in the current status (REF scenario), groundwater pumping is the most electricity-intensive activity in the basin. Over the modelling period of 2020-2050, groundwater pumping requires an average of about 470 GWh annually as shown in Figure 29. Once the second phase of the desalination plant starts operating in 2030 (all other scenarios, DES, WWR, IWP, INS), desalination will overtake groundwater pumping as the most electricity-intensive activity in the basin. In the first phase, the desalination plant will consume an average of 350 GWh annually to desalinate and convey water. In the second phase, this will increase to over 600 GWh annually of which water conveyance is about 140 GWh annually. Other activities such as surface water conveyance and wastewater treatment and reuse require a relatively low amount of electricity. This explains why the graphs of the four scenarios (DES, WWR, IWP and INS) in Figure 29 have a very similar appearance. Surface water conveyance primarily relies on the difference in elevation and limited pumping is applied - requiring only 28 GWh annually. For wastewater treatment, primary treatment is assumed in the (REF, DES and IWP) scenarios. Secondary treatment (activated sludge) [254] is assumed only for cases involving reuse of the treated wastewater (WWR and INS scenarios).

With secondary treatment, the annual energy demand for wastewater treatment increases from 4 GWh in REF to 35 GWh in the WWR and INS scenarios. In contrast to desalination, treated wastewater is assumed to be used in the agricultural area close to the treatment plants. This means that the energy required to convey the treated water is negligible.

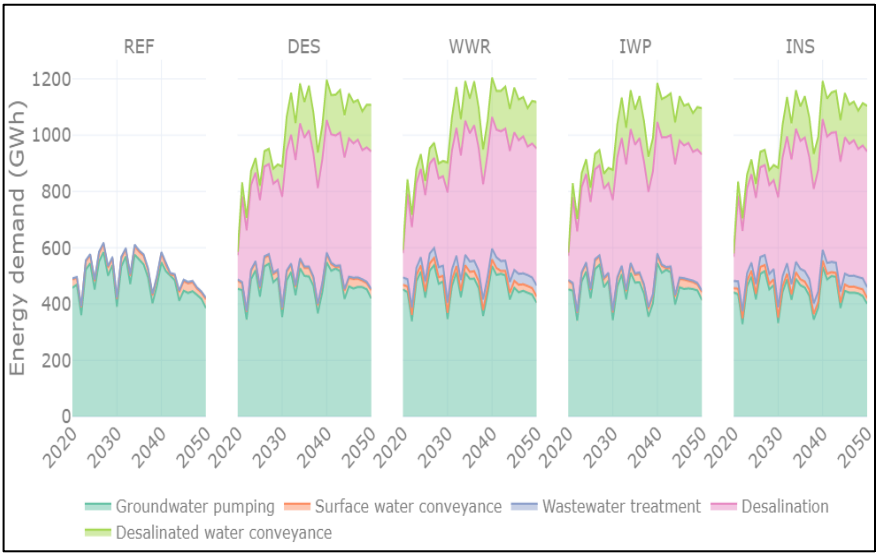


Figure 29. Energy requirements for different activities across all scenarios[10]: [Reference (REF), Desalination (DES), Desalination with Wastewater Reuse (WWR), Increased Water Productivity (IWP) and Integrated Strategies (INS).]

In summary, the analysis shows that sustaining the agricultural activity in shared groundwater basins is not a management challenge for the agricultural sector alone, it is equally a challenge for other sectors (e.g. water and energy). It is worth noting that in arid areas such as the NWSAS and Souss-Massa basins, groundwater pumping consumes a significant amount of energy. The arid climate, the overexploitation of water for irrigation purposes, and the drawdown of water levels are among the reasons that result in the high energy demand. The quantification of such demand is a valuable input to inform shared management policies. Nevertheless, such quantification would not be possible without consideration of the energy-water-agriculture nexus and the

[10] The graph shows the energy demand for pumping based on the water abstraction estimated by WEAP in each year. The splikes and dips are due to differences in irrigation demand which varies between years due to the variation in climate conditions (e.g temperature) which then results in differneces in the evapotranspiration, irrigation demand and energy demand for pumping.

cooperation of different stakeholders and sectors throughout the model development process.

3.3.3 Spatially explicit least-cost electricity supply technologies for irrigation in water-scarce regions.

The most cost-effective strategy for powering groundwater pumping varies from one region to another. The spatial techno-economic analysis developed in the dissertation helps to have a good understanding of the least cost strategy in each location of the NWSAS Basin. It also provides insights on the key parameters affecting the least cost option. The Levelised Cost of Electricity (LCOE) is used as a metric to compare different supply options.

Mapping the least-cost supply option (Figure 30) shows most locations are coloured either red or purple which reflects the use of diesel generators in Algeria and Tunisia, and grid electricity in Libya. It should be noted that about 60% of electricity generation in Libya is from Natural gas and the remainder from oil products [255]. The dominance of fossil fuels in powering the pumping activity in the region is very clear. This can be attributed to the cheap fossil fuel prices in the three countries due to high subsidies. Additionally, high energy subsidies make the penetration of renewable energy technologies, at their current cost, very challenging. For example, at the time of this study, the cost of one litre of diesel in Algeria was USD 0.17 while in Tunisia it was USD 0.62 [234] and the price of electricity was about USD 0.168 / kWh[11] [235].

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[11] As of Oct 2022, the cost of one litre of diesel in Algria increased to USD 0.2 (22% increase compared to the values assumed in this study) while it increased slightly in Tunisia to USD 0.642 (4% increase). However, in Libya the price droped by 73% to about USD 0.03 /litre of diesel. The electricity price in Algeria inceased to 0.038 USD/kWh (36% increase) while in Tunisia it decreased to 0.065 USD/kWh (-35%) and in Libya to 0.004 USD/kWh (-98%) [256], [257].

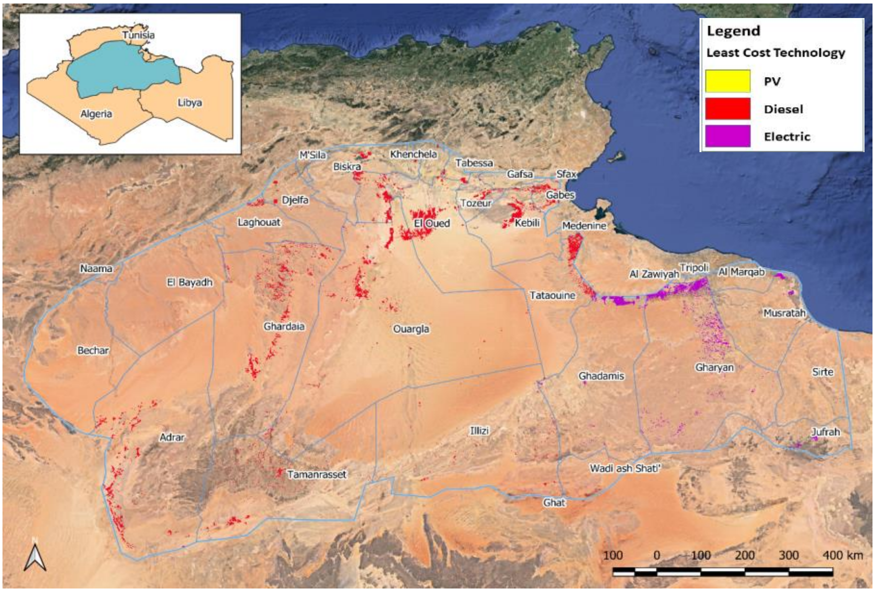


Figure 30. Least cost electricity supply option for pumping irrigation in the NWSAS region.

To facilitate renewable energy deployment in regions such as the NWSAS, renewable costs and subsidy structures need to be revised. This leads to the next research question of this dissertation.

3.4 How can the consideration of the energy-water-agriculture nexus accelerate the low-carbon transition in the agricultural sector?

The agricultural sectors in many developing countries rely heavily on fossil fuels to power different activities such as groundwater pumping as has been demonstrated in the previous sections. In the long term, this practice has an environmental impact and it also influences farmers' revenues due to changes in fuel prices and increased pumping demands. In many cases, governments subsidise fuel prices for farmers to support the agricultural sector, but this shifts the economic burden to the government's budget.

Renewable energy solutions, especially solar pumping, have demonstrated their competitiveness. However, the economic competitiveness of the low-carbon solutions varies between locations. Site-specific inputs such as pumping demand, solar resources, and fossil fuel costs at the site are key parameters affecting the competitiveness of renewables.

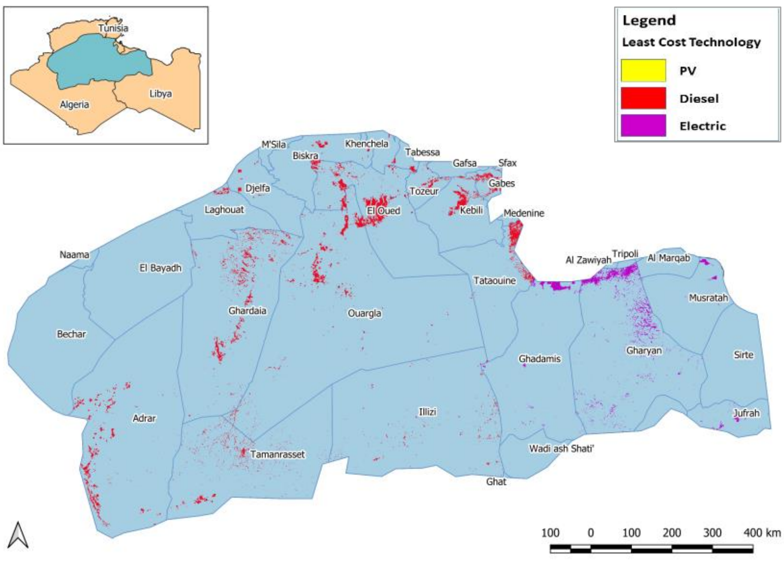
This dissertation first explores the impact of fossil fuel subsidies and the capital costs of renewable technologies on the competitiveness of solar pumping (sub-section 3.4.1). This is based on the NWSAS case (paper III). Second, the impact of time on the transition is explored as are the benefits that could be achieved by accelerating the transition (sub-section 3.4.2). This sub-section draws insights from the Souss-Massa case (paper IV).

3.4.1 **The relative importance of removing fossil fuel subsidies versus reducing the capital cost of renewable technologies**

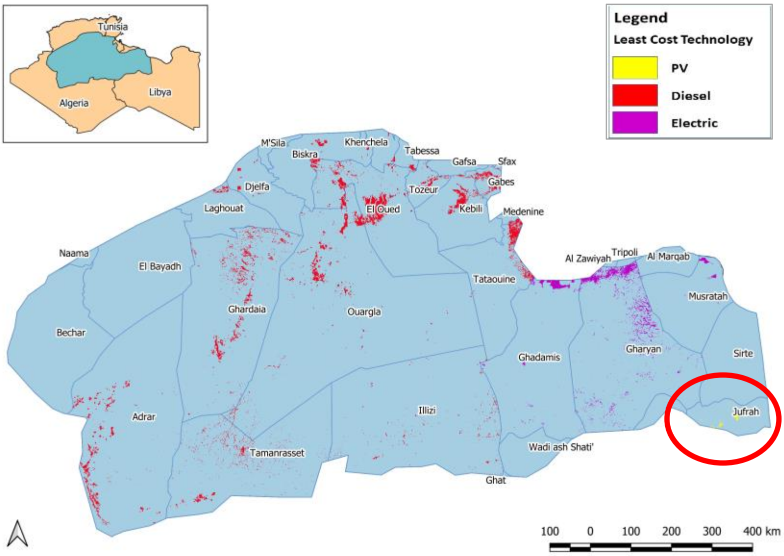
In this section, the sensitivity scenarios are designed to study the impact of two factors on the LCOE at each location of the NWSAS: **a)** Capital Cost (CAPEX) of renewable solutions, and **b)** Fossil fuel subsidy level. The changes are introduced in three phases or levels with a total of nine scenarios (see Table 14).

At CAPEX level 1:

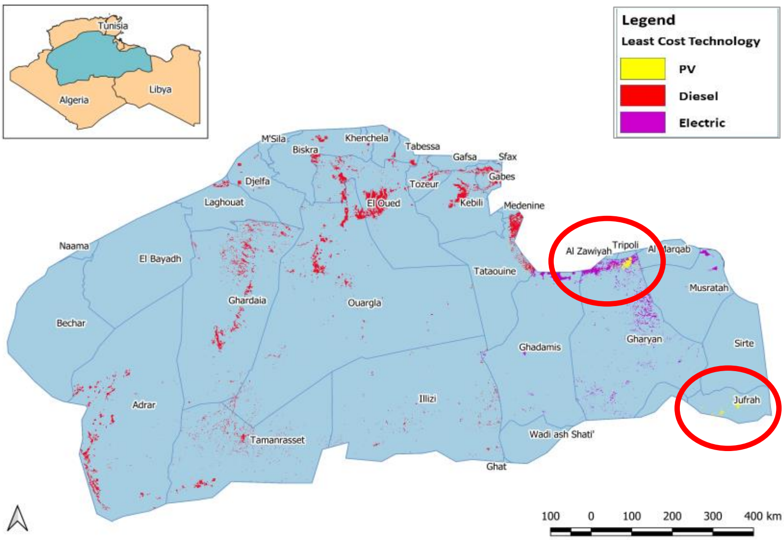
At this level, renewable capital costs are the same as the current market price of 1,140 USD/kW for solar PV and 1,300 USD/kW for small-scale wind turbines. Three fossil fuel subsidy levels are explored: the current level, 30% reduction and 50% reduction. At the current CAPEX and subsidy level, only fossil fuel options are cost-competitive (Figure 30-a). Removing 30% of fossil fuel subsidies mean solar PV starts to be competitive in Jufrah (Libya) (Figure 30–b). With 50% subsidy removal, solar PV also starts to be part of the mix in Gharyan (Libya), especially in the northern part (Figure 30–c). This change can be attributed to two factors. First, is the relatively higher solar radiation in those provinces (about 2,000 kWh/m^2 per year). Second, is the high irrigation water demand which means more energy for pumping and therefore lower LCOE value for solar PV. The small-scale wind turbine cannot compete in any case, due to its high capital cost and the relatively low wind speed at the locations considered.



a) **CAPEX level 1 - Fuel Level 1(**Current subsidy level)



b) CAPEX level 1 - Fuel level 2 (30% increase compared to level 1)



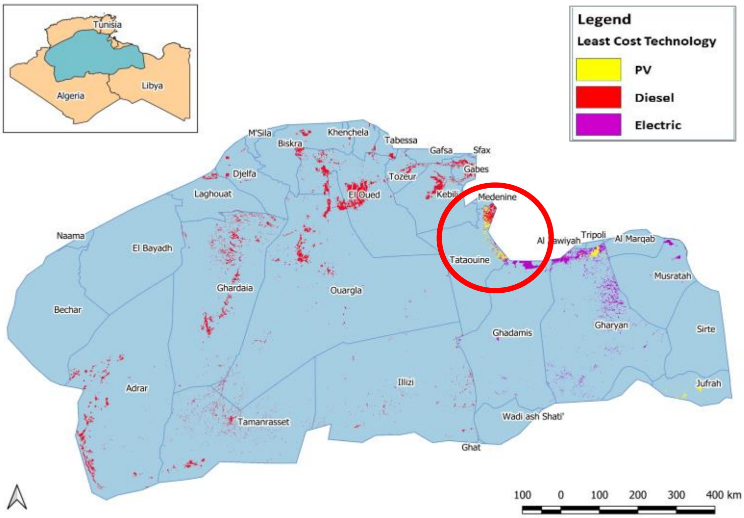
c) CAPEX level 1 - Fuel level 3 (50% increase compared to level 1)

Figure 31. Comparison between the electricity supply options at CAPEX level 1 for three levels of fuel subsidy.

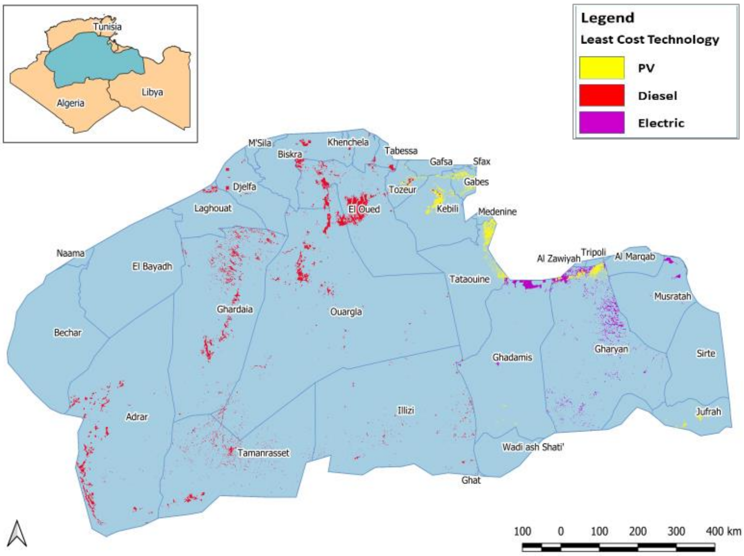
At CAPEX level 2:

At this level, renewable capital costs are reduced by 15% to 970 USD/kW for solar PV and 1,105 USD/kW for small-scale wind turbines. This change will be reflected first in the location where fuel prices are higher (lower subsidy level) which is Tunisia [234]. With costs assumed at this level, solar PV starts to form part of the energy mix in Tataween (south of Tunisia) as shown in Figure 32-a. Tataween has higher solar radiation than other Tunisian provinces reaching 1,900 kWh/m^2 per year.

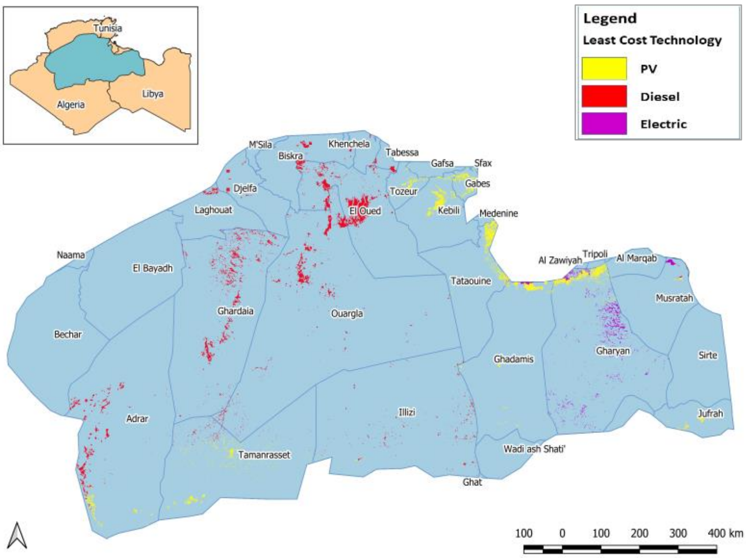
Increasing fossil fuel costs by 30% will be enough to make PV the preferable option in most of Tunisia as shown in Figure 32–b. This is again due to the already low subsidy levels in Tunisia (high fuel prices). The Algerian part of the NWSAS regions will require further removal of fossil fuel subsidies, up to 50%, before PV becomes competitive. The southern Algerian provinces such as Adrar and Tamaneassat have the highest solar radiation in the region. These provinces are the first in which solar technology starts to be present on the Algerian side (Figure 32–c). It is noteworthy that Adrar and Tamaneassat are the provinces with the highest annual irrigation requirement (Figure 27).



a) CAPEX level 2 - Fuel Level 1 (Current subsidy level)



b) CAPEX level 2 - Fuel level 2 (30% increase compared to level 1)

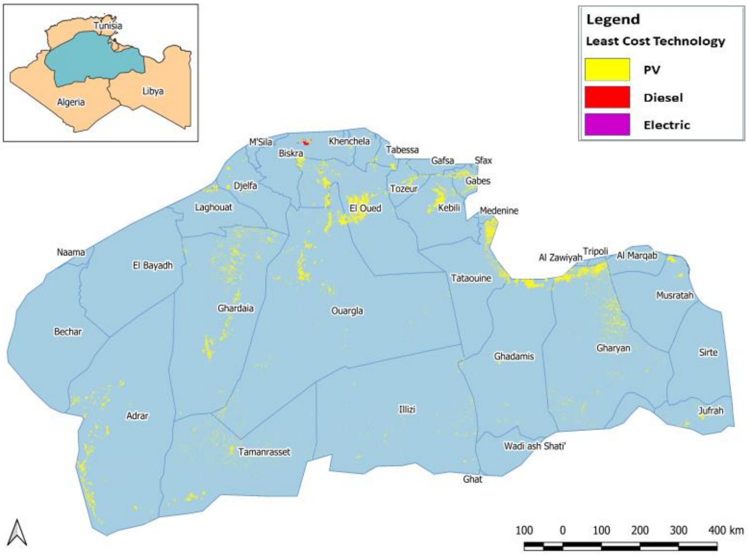


c) CAPEX level 2 - Fuel level 3 (50% increase compared to level 1)

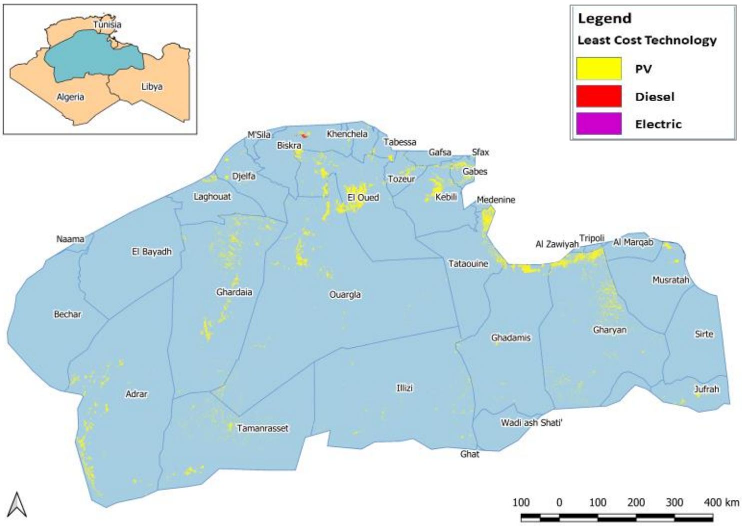
Figure 32. Comparison between the electricity supply options at CAPEX level 2 for three levels of fuel subsidy

At CAPEX level 3:

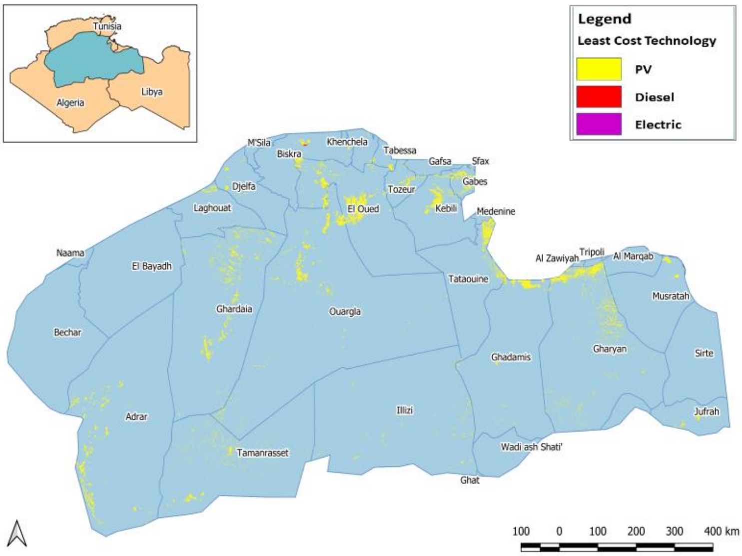
In this third and final level, the capital cost of renewables is further decreased to 680 USD/kW for solar PV and 910 USD/kW for small-scale wind turbines. At this CAPEX level, solar PV is the least cost supply option for farmers in almost the entire NWSAS region even at the current subsidy level for fossil fuels as shown in Figure 33. Despite this large reduction in capital cost, wind is still not cost-competitive in the region.



a) CAPEX level 3 - Fuel Level 1 (Current subsidy level)



b) CAPEX level 3 - Fuel level 2 (30% increase compared to level 1)



c) CAPEX level 3 - Fuel level 3 (50% increase compared to level 1)

Figure 33. Comparison between the electricity supply options at CAPEX level 3 for three levels of fuel subsidy.

This analysis shows that the competitiveness of renewable technologies (mainly solar PV) is more sensitive to changes in technology cost than to fossil fuel subsidies. This means that the transition to low-carbon solutions in the agricultural sector requires that technology costs be carefully considered before thinking about subsidy removal which could cause social and political tensions. Developing renewable energy support schemes for farmers in regions like the NWSAS is a key policy question for decision-makers if renewable technologies are to be made affordable for middle to low-income people. One option might be redirecting some of the fossil fuel subsidies towards reducing the cost of solar systems for farmers. The spatial analysis shown here can help in setting implementation priorities based on which area shifts to solar pumping first and has better solar potential and/or requires more water for irrigation. The analysis also explains why farmers are still willing to pay the operational costs of diesel generators or grid electricity and do not shift to a “free” source of energy like solar. They simply cannot afford the high investment cost of renewables.

Nevertheless, it is important to stress that the use of solar technology for irrigation comes with a significant risk of aggravating groundwater exploitation. This is particularly true in areas where abstraction limits are non-existent or difficult to impose as in the case of the NWSAS. Once the investment cost is paid, PV pumps have almost zero operational cost. In many cases, this has motivated farmers to intensify their production, expand irrigation and shift to more water-intensive crops [253]. A clear example is the Punjab state in India, where electricity subsidies to support food production have resulted in over-abstraction and lowering of the water table [14]. This key policy question underlines once again the importance of close collaboration among the agriculture, water and energy sectors to ensure a sustainable transition towards renewable technologies.

3.4.2 Does time matter? What benefits can be achieved by accelerating the transition to low-carbon solutions

To address this question, the dissertation focuses on the Souss-Massa Basin (paper IV). Here groundwater pumping is currently the activity with the highest energy demand and the second-highest after 2030 (when phase II desalination will start) as shown earlier in section 2.3.4. Butane powers about 20% of the pumps, while solar powers only 10% of the pumps and the remaining 70% of pumps are powered by the national grid. Different decarbonisation strategies are studied to phase-out butane use in groundwater pumping. Two criteria are selected to develop the sub-scenarios (Table 15). The first is how fast the phase-out of butane should take place? And the second is how much solar pumping should be deployed? The sub-scenarios or the strategies are then compared based on economic and environmental metrics: **a)** the total cost (in million Moroccan Dirham “MAD”), and **b)** the CO_2 emission levels (in MtCO2).

The system cost shown in this part encompasses the cost of the electricity generation from the national grid, butane subsidies, PV installation costs and the re-installation cost of PV (for the units that will reach their lifetime before the end of the modelling period). The system cost and the environmental impacts considered in the analysis are from the government’s perspective, not the end-users' (farmers).

The total system cost for different sub-scenarios representing PV adoption levels of 10%, 20%, 40% and 60% is shown in Figure 34. Each sub-plot shows the costs at three different butane phase-out end years (none, by 2040 and by 2030). It can be seen that with no phase-out the cumulative subsidy budget totals MAD 6.6 billion. The late phase-out by 2040 reduces this cost to about MAD 2.2 billion while the early phase-out further reduces the subsidy burden to about MAD 1.2 billion. This is shown by the green bars in Figure 34 that represent the butane subsidy levels. This means that accelerating the transition away from butane can potentially save the Moroccan government about MAD 4.4 or MAD 5.4 billion for early and late phase-out, respectively, which is equivalent to USD 444-554 million[12].

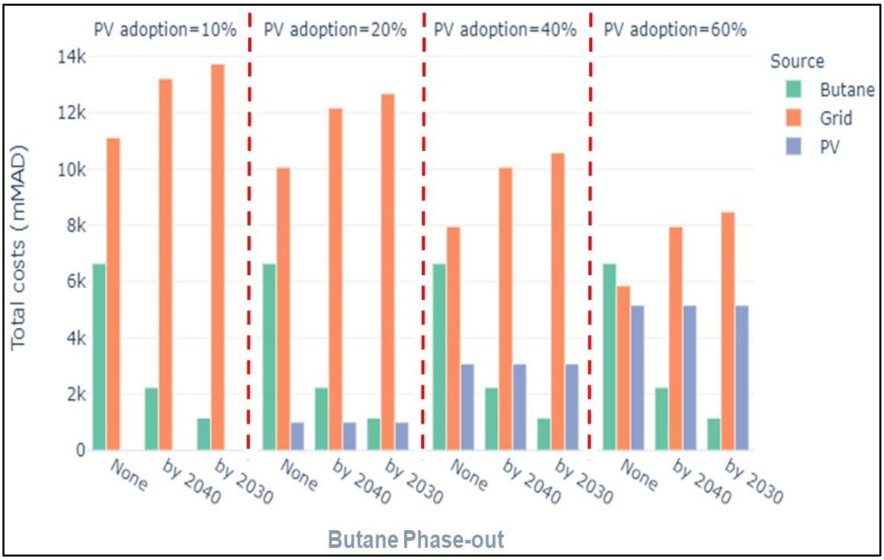


Figure 34. Total system cost under different PV adoption levels

PV adoption (10%, 20%, 40% and 60%) and different butane phase-out scenarios (None, by 2040, and by 2030). The bars show the cost of each of the three pumping technologies (butane, grid and PV) for each case.

The transition from butane means changing to either solar PV or grid electricity. Knowing that the Moroccan grid is heavily dependent on fossil fuels, the total emissions (in $MtCO_2$) for each scenario are estimated based on the emissions of both butane-driven pumps and grid-driven pumps (see Table 16).

Figure 35 shows a comparison between the 12 scenarios. The x-axis shows the total emission level (in $MtCO_2$) under each scenario and the y-axis shows the total cost of the system (in MAD million) for the entire modelling period 2020-2050. Theoretically, the best

[12] Based on 5 years (2018-2023) average exchange rate of USD 1 = MAD 9.92.

scenario (for the government of Morocco) is the one with the least cost and least emissions. From the economic perspective, the current situation (no phase-out scenario) will result in a very high system cost (about MAD 17.8 billion or USD 1.8 billion) while the early phase-out by 2030 will have the lowest system cost (about MAD 14.9 billion or USD 1.5 billion). The late phase-out by 2040 will have a slightly higher cost (about MAD 15.5 billion or USD 1.6 billion) compared to the early phase-out. This is reflected in the distribution of the three colours in the figure. From the environmental perspective, the higher the share of PV, the lower the emissions. This can be seen by comparing the different bubble sizes and the corresponding emission levels. The current situation, with no phase-out and 10% PV share only, results in a high system cost and environmental damage. This can be seen as the worst-case scenario. The fast transition or the early phase-out of butane by 2030 and high investments in solar pumping to a 60% level is shown to be the best scenario. This fast transition has the potential to save the Moroccan government about MAD 3 billion (or USD 302 million) and cut about 6 $MtCO_2$ of emissions annually from the agricultural sector in Souss-Massa.

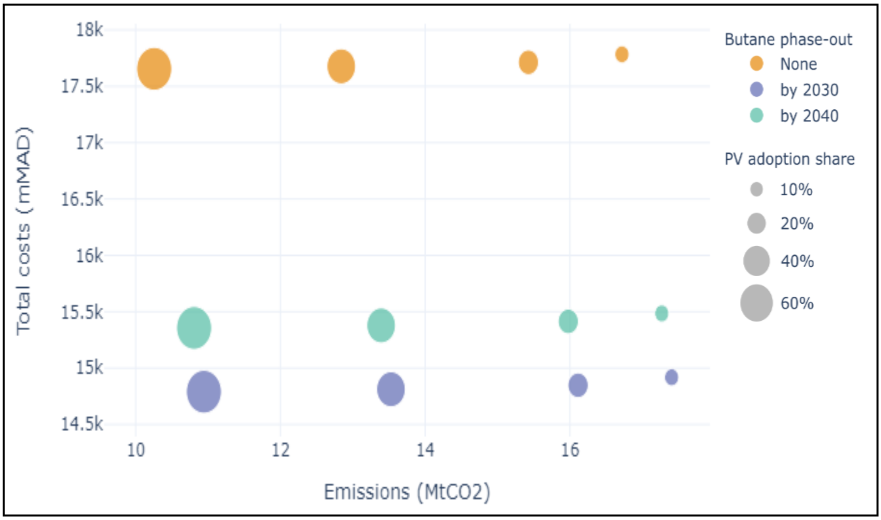


Figure 35. Comparison between different butane phase-out and PV adoption scenarios.

The x-axis shows the total emissions and the y-axis shows the total system cost (butane, grid and PV).

In summary, it can be concluded that the transition to a low-carbon economy in the agricultural sector requires cross-sectoral effort. The traditional thinking of fossil fuel subsidy removal is not enough to convince farmers to shift to low-carbon alternatives such as solar pumping. Governments should develop new support schemes that make renewables affordable to low and middle-income farmers. Such changes should take place sooner rather than later. The earlier the transitions are made, the higher the gains for governments and the environment.

4 Conclusions

This chapter presents the overall concluding remarks of this dissertation. It starts by mapping the research questions to the insights; then it gives an overview of the key thesis contributions; before it considers limitations and future work and finally makes some observations on the impact of this dissertation.

4.1 Objective, research questions and insights

The **objective of this thesis is to support the coordinated management of shared water resources. The WEF-nexus approach is used to motivate cooperation, quantify the benefits of coordinated management and identify trade-offs in the optimal use of resources**.

In conclusion, this objective is fulfilled, primarily via the insights given to the research questions explored as shown in the discussion of each research question below. The benefits of cooperation have been quantified via the open-source models developed to study a multitude of scenarios in relevant case applications. The methods, tools and insights derived from this work have been used to disseminate the WEF-nexus and coordinate management concepts in different regions. This thesis informed policymakers in the study basins through a series of workshops, high-level meetings, webinars, policy briefs and technical reports. Combined, these activities have indeed supported and motivated the coordinated management of shared water resources.

RQ1. What role can the energy sector play in motivating cooperation in transboundary water management?

This thesis explored different dimensions of cooperation and different areas where the energy sector can contribute to such cooperation. The methodology and the results presented in sections 3.1.1 and 3.1.2 quantified the benefits of cooperation in the Drina transboundary river basin (paper I). The energy sector can play an important role in encouraging different governments to work together and maximise synergies in shared water basins. The potential gains in terms of electricity generation (direct impact) and enhanced electricity trade (indirect impact) can be seen as two examples of the potential benefits of transboundary cooperation. Additionally, section 3.1.3 relating to the Drin River Basin (paper II) explored the role of hydropower or the energy sector in mitigating the risk of extreme climate events (i.e. floods). This dissertation showed that the energy sector can play an important role in mitigating the risk of floods not only by increasing the share of renewables but also by how it operates renewables. The analysis showed how imposing "flood-smart" operational rules in hydropower plants can potentially provide substantial storage capacity without compromising the security of electricity supply. The findings of this dissertation were used to inform the dialogue between stakeholders in the Drina [243], [258] and Drin [259], [260] basins and promote cooperation.

RQ2. What risks and opportunities emerge from the interplay between climate and renewable energy in shared basins?

Taking the case of the Drin River Basin and the cascade of hydropower plants, this thesis explored the impact of climate change on the security of electricity supply in an electricity system that is highly dependent on hydropower (Albania). The methodology, the results and the appended paper II highlighted the vulnerability of the electricity system of the Drin countries to climate change. The insights drawn from this analysis showed that VRE (solar and wind) can increase the preparedness of nations for climate change and increase the security of electricity supply.

RQ3. What benefits can the consideration of the energy-water-agriculture nexus bring to shared groundwater management in water-scarce areas?

Considering the cases of the NWSAS and the Souss-Massa Basin in North Africa, this dissertation developed an integrated energy-water-agriculture nexus model to explore selected nexus questions. The methods and the tools presented in chapter 2 and papers III and IV, highlighted the importance of the nexus approach in addressing overexploitation and poor management of groundwater sources. The modelling tool provided a better understanding of the basin-wide irrigation and energy requirements. Coupling the agricultural activity with water and energy system characteristics in an integrated model allowed the exploration of different scenarios and the quantification of their impact across sectors. It would not be possible to obtain such insights without consideration of the three systems (agriculture, water and energy) together. For the scope of this dissertation, the focus was on on-farm agriculture activities - mainly irrigation. The spatial nature of the analysis made it possible to obtain a more accurate picture of the energy sources in the basin (i.e. solar radiation) and the least-cost electricity supply options in each irrigation area.

RQ4. How can the consideration of the energy-water-agriculture nexus accelerate the low-carbon transition in the agricultural sector?

This dissertation focused on two dimensions to address this question. First, it explored the impact of fossil fuel subsidies and renewable technology costs on the transition to low-carbon solutions. Second, it studied the temporal dimension and explored the economic and environmental impact of having different time-frames to achieve such a transition. The results presented in section 3.4.1 and paper III (the NWSAS), highlighted that the transition to low-carbon solutions is more sensitive to the costs of renewables than to fossil fuel subsidies. The insights drawn from this study showed that setting up supporting schemes for renewables is critical for governments if they want to motivate middle and low-income farmers to move towards solar pumping.

The results presented for the Souss-Massa case in section 3.4.2 and paper IV were used to address the importance of the temporal dimension. The insights drawn from the different scenarios revealed that it is not enough just to shift to low-carbon solutions. It is equally crucial to accelerate this transition to low-carbon solutions if high economic and environmental consequences are to be avoided. In the case of the Souss-Massa Basin and under the assumptions of this study, accelerating the transition could potentially save the Moroccan government about MAD 4.4 – 5.4 billion (or USD 444-554 million). The benefits could even be larger if a national transition scheme were set in place.

4.2 Thesis contribution

This dissertation makes several contributions to academic knowledge. Table 21 summarises the key contributions of this dissertation, which, at the time of publication, were the first of their kind. Although the list is not exhaustive, it gives an overview of the advancements in broader academic literature and the countries studied.

Table 21. Thesis contributions.

Methodological advances
• A new methodological approach was implemented in the Open Source energy MOdelling SYStem (OSeMOSYS) by introducing a hydrological system and linking it to the standard electricity system model. This approach allows for a better representation of water availability and for modelling the cascade effect on hydro generation. • A new methodological enhancement was added to the storage functionality in the OSeMOSYS by introducing new methods to capture hydropower plants' operational rules. • A new mixed-method approach was introduced to the water-energy-food nexus methods, combining the standard TBNA nexus method and the Robust Decision Support (RDS). • Contributed to the development of a GIS-based methodology to estimate the electricity requirement for groundwater pumping for irrigation. • Open-access energy models were developed and codes were published on GitHub and in open-access scientific journals. This gives accessibility to the approach, codes and input data, thus enhancing transparency and creating opportunities for reproducible research.

New data and Insights
• Quantifying the benefits of cooperation in terms of annual electricity generation gains from hydropower plants in the Drina River Basin. • Estimated the annual electricity requirement for pumping in the entire region of the NWSAS. This was done for the first time at the basin level. • Quantified country-specific water and energy implications of agricultural activity in the NWSAS region. • Estimated the impact of climate change on the security of electricity supply in Albania and North Macedonia. • Developed spatially explicit data on the irrigation demand and electricity demand in Souss-Massa and NWSAS. In both cases, this was done for the first time for an entire basin scale.
Applied analytical advances (or impacts)
• First multi-country electricity system model for the Drina River Basin using OSeMOSYS, in which the full electricity systems of the three riparian states are presented and the cascade of the hydropower plants in the Drina Basin is detailed. • The first open-source model for the Drin River Basin to represent the details of the hydropower plants in the basin and connect them with the full electricity system in each of the riparian states (Albania, North Macedonia, Kosovo and Montenegro). • First spatially-explicit energy model that covers the entire region of the NWSAS and links the electricity system with the irrigation and agricultural activity in each province. • Spatially explicit model for the Souss-Massa Basin and year-by-year estimation of the energy/electricity requirements for

various agriculture-related activities (irrigation, desalination, wastewater treatment and conveyance).
Contribution to open-science (FAIR principles):
This thesis contributes to open-science and complies with the FAIR principles [261] (Findable, Accessible, Interoperable and Reusable) in the following ways: • The sources' codes and datasets can be found and accessed in open Github repositories [196], [197], [247]. • Each application is supported by a scientific publication and code documentation to give a detailed explanation of the methodologies, references to the data sources, assumptions and required procedures. This facilitates the interoperability and reusability of the methods and tools developed. • The scripts developed in this dissertation use an MIT-licence [262] which is an open-source software licence. This licence permits unrestricted use, distribution, and reproduction of the codes insofar as the attribution is preserved. This means giving stakeholders in the studied basins or other researchers express permission to reuse the codes for any purpose. • In all case applications, a huge effort was made to collect local data directly from stakeholders. Such data is often not available via online sources or if available it is not up to date. For example, the operational rules of Drin River HPPs, and the groundwater depth in each province of the NWSAS Basin. This dissertation makes such data open and available for any researchers' future work.

4.3 Limitations and recommendations for future work

This thesis has explored the role of the energy-water and agriculture nexus in the sustainable management of shared water resources. Various study areas, quantification tools and scenarios were used to achieve the aim of this research. This study laid a foundation for future work that will be able to address some of the limitations of the current work.

In terms of models and data, the models developed in this dissertation are populated with site-specific data to the extent possible. However, there are still important data gaps to be filled in future work. For example, improving the spatial representation of the national grid to provide a better mapping of farms' proximity to the grid could help explore the economics of selling the excess electricity to the national grid during off-peak hours (paper III and paper IV). Also, improving the spatial and temporal resolution in the models (paper I and paper II) could improve the representation of intermittent renewable energy technologies (solar and wind). Another dimension could be the integration of the energy model (OSeMOSYS) with flood damage modelling tools as was done briefly in a follow-up study in the Drin Basin [132]. Such integrations can provide a better understanding of the synergies between hydropower operation and floods in terms of mitigating flood damage and reducing the area flooded especially if a wider range of operational rules is explored. Another example could be presented from the NWSAS case (paper III). The integration of the GIS-based model with the hydrological model of the basin could open the door to exploring a wider range of scenarios such as exploring the impact on groundwater level.

In terms of the objective function, it should be noted that the quantification approach in this dissertation is based on the least cost objective. This is true for the optimisation using OSeMOSYS (paper I and paper II) and the GIS-based electricity model (paper III and paper IV). Considering multi-criteria optimisation, as developed by [69], could help in the consideration of new horizons in respect of policy-making criteria (e.g. environmental and social aspects).

In terms of climate change representation, this dissertation explored the impact of climate change on hydropower (paper III). However, this could be expanded to consider a wider range of climate scenarios. Also to explore climate change impact on groundwater resources in more detail, especially in water-scarce regions (paper III and paper IV).

Where electricity trading was considered, a simplified representation of electricity interconnectors was used (in paper III). This could be considered in greater detail to account for the existing and planned cross-border interconnections and to provide a better understanding of electricity flow in each direction. This could provide a better overview of regional electricity trade and help to quantify the synergies and trade-offs between electricity trading and the operation of hydropower plants and/or investments in non-hydro renewables such as solar and wind.

In terms of uncertainty and sensitivity analysis, this dissertation briefly studies the sensitivity (local sensitivity analysis) of the results to selected model inputs (e.g. fossil fuel subsidies and the cost of renewables in paper III). A proper uncertainty analysis and a wider sensitivity analysis (global sensitivity analysis) could be conducted in future work. This could, for example, explore the sensitivity of results to key input parameters such as the discount rate, fossil fuel prices, electricity demand, wholesale electricity prices and a wider range of hydropower plants' operational rules, to name just a few. The uncertainty in climate projections cannot be ignored [263] [264]. The robustness of the power sector could be further explored in any future work by considering a broad range of climate projections from different GCMs and RCMs and using different hydrological models.

4.4 Impact of this thesis

This dissertation has presented a number of real-life applications of the nexus approach for addressing sustainable development questions. This work would not be possible without close collaboration with international organisations such as the United Nations Economic Commission for Europe (UNECE), Global Water Partnership (GWP) and the United Nations Food and Agriculture Organisation (FAO).

The collaboration with UNECE on the Drina transboundary Nexus assessment, with UNECE and GWP on the NWSAS and Drin nexus assessment and with FAO on the Souss-Massa nexus study, goes beyond just the analytical work. All these projects had an embedded goal of disseminating the nexus knowledge and awareness among government officials, local experts and academia. The author contributed to the preparation and facilitation of nexus dialogues which occurred in different formats such as workshops and online focus group meetings.

Beyond the local context, the work developed in this thesis was also used to promote transboundary cooperation at high-level meetings such as the UNECE task force meetings in 2016 [258] and 2017 [265] and the meeting on "*Promoting an integrated and inter-sectoral approach to water management in the Mediterranean region*" organised by UNECE and the Union for the Mediterranean in 2019 [266]. Additionally, the work of this thesis is used to inform the international community and is used as an example of sustainable water and energy solutions by the United Nations [267].

The work developed in this thesis contributed to showcasing the UNECE-TBNA methodology and shaped different chapters of UNECE publications such as: *Assessment of the water-food-energy-ecosystems nexus and benefits of transboundary cooperation in the Drina River Basin* [16]*, "Reconciling resource uses: Assessment of the water-food-energy-ecosystems nexus in the North Western Sahara Aquifer System Part A - Nexus Challenges and Solutions"* [129] and *"Phase II - Nexus Assessment for the Drin River Basin"* report [132]. Furthermore, the methods and insights of this dissertation informed other reports such as: "*Methodology for assessing the water-food-energy-ecosystems nexus in transboundary basins and experiences from its application: Synthesis*" [30]. The agricultural aspects of this work contributed to one of the key background papers for the CGIAR, in their bi-annual science forum held in 2018 [268].

In addition to that, the author contributed to capacity-building activities where beneficiaries in the Drin Basin countries [260] and the Souss-Massa Basin were trained on the nexus framework and the use of modelling tools. Furthermore, the works developed in (paper III) and (paper IV) were used to introduce the water-energy-food nexus in the NENA region through a series of webinars organised by FAO [269] [270]. In respect of the contribution to the water-energy-food nexus research field, the work of this thesis was presented at scientific conferences such as the European Geosciences Union (EGU) General Assembly 2017 [271], the Fourteenth IAMC Annual Meeting 2021 [272] and the European Climate and Energy Modelling Platform (ECEMP) 2022 [273].

Throughout the doctoral studies period, the author contributed to different courses at KTH, helping to build awareness among the students about the importance of the nexus and training them on the use of OSeMOSYS. The author was also invited as a guest lecturer on the nexus topic at the master program organised by the International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM) in Zaragoza [274]. The author also supervised several master's level thesis studies that focused on the water-energy-food nexus in different contexts [148], [275]–[277].

Furthermore, the author contributed to the open-source energy modelling community. The author led the development of “the Model Management Infrastructure (MoManI)” which is used as an interface for OSeMOSYS. The use of the interface is supported by teaching materials and a case study (Atlantis). MoManI is among the tools used by the United Nations Department of Economic and Social Affairs (UNDESA) and the United Nations Development Programme (UNDP) to help countries assess sustainable development policy options [278]. The tool is also used in schools such as KTH and the Joint Summer School on Modelling Tools for Sustainable Development [279] and the Energy Modelling Platform (EMP) capacity-building activities, which since 2017 have welcomed hundreds of participants from all over the world [280].

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