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Methodology for multi-actor and multi-scale decision support for Water-Food-Energy systems

Amaya Saint-Bois

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Doctorat de l'Université de Toulouse

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Méthodologie d'aide à la décision multi-acteur et multi-échelles pour les systèmes nexus eau-énergie-alimentation

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Méthodologie d'aide à la décision multi-acteur et multi-échelles pour les systèmes nexus Eau – Energie – Alimentation

Cette étude présente une méthodologie générique multi-acteurs et multi-niveaux pour la gestion des systèmes nexus eau-énergie-alimentation. Les systèmes nexus eau-énergie-alimentation sont des systèmes où l'eau, l'énergie et l'alimentation interagissent et présentent des synergies et des compromis à différentes échelles spatiales et temporelles. Leur gestion est menée par des décideurs provenant de secteurs divers, qui interviennent à des niveaux de décision variés. Ces systèmes sont complexes et le niveau opérationnel ne peut être négligé pour concevoir des stratégies de gestion adéquates.

Ce travail présente la première méthodologie destinée aux systèmes nexus eau-énergie-alimentation, qui combine des simulations opérationnelles et intégrées de systèmes multi-agents avec des méthodes d'aide à la décision stratégique. Les simulations à échelles opérationnelles alimentent des outils d'aide à la décision stratégique. La méthodologie a été appliquée à des problèmes d'utilisation des terres à l'échelle de la parcelle agricole. Pour chaque territoire étudié, le nombre de combinaisons possibles d'allocations de stratégies d'utilisation des terres aux parcelles est égal au nombre de stratégies d'utilisation des terres considérées pour chaque parcelle, exponentiel le nombre de parcelles du territoire. Des méthodes d'aide à la décision multicritères basées sur des simulations Monte Carlo ont été conçues afin de pouvoir trouver des solutions de gestion pour des grands territoires (plus de 1000 parcelles) pour lesquels plus de deux stratégies d'utilisation des terres sont considérées sur chaque parcelle. Une méthode d'optimisation multi-objectif a été conçue pour produire des scénarios d'utilisation des terres optimisés à l'échelle du territoire.

La méthodologie a été appliquée à un territoire agricole d'environ 800 km² et 15224 parcelles situé en aval du bassin versant de l'Aveyron en France. Le bassin versant subit du stress hydrique et se trouve dans l'une des régions les plus ensoleillées de France. La production d'énergie renouvelable sur des terres agricoles apparaît comme un moyen de répondre aux objectifs nationaux de production d'énergie renouvelable et de progresser vers des systèmes et des régions agricoles durables. L'installation d'unités de production d'énergie renouvelable sur des terres agricoles confrontées au stress hydrique est une parfaite illustration d'un système nexus eau-énergie-alimentation pour lequel une approche holistique est requise. Les fonctionnalités de la plateforme multi-agents MAELIA (modélisation des systèmes socio-agro-écologiques pour l'évaluation intégrée des paysages), développée par des chercheurs français pour simuler des systèmes agro-hydrologiques complexes, ont été étendues et MAELIA a été utilisée pour simuler la dynamique des systèmes nexus eau-énergie-alimentation au niveau opérationnel. Trois méthodes qui combinent la procédure d'analyse hiérarchique (méthode de prise de décision multicritères) avec des simulations Monte Carlo ont été conçues. La première se base sur des indicateurs à l'échelle de la parcelle pour émettre des décisions locales ; elle sélectionne des stratégies d'utilisation des terres qui optimisent des indicateurs au niveau de la parcelle. Les deux autres méthodes basent leurs prises de décisions sur des indicateurs régionaux. La première identifie le meilleur scénario régional d'utilisation des terres parmi un ensemble de scénarios connus et la deuxième explore l'espace combinatoire des allocations de stratégies d'utilisation des terres à l'échelle de la parcelle et sélectionne une combinaison qui optimise les critères au niveau régional. Une méthode d'optimisation multi-objectif basée sur la programmation linéaire en nombres entiers mixtes (MILP) et la programmation par objectifs a été développée avec le logiciel IBM ILOG CPLEX pour produire des scénarios optimisés à l'échelle régionale, qui allouent des stratégies d'utilisation des terres à l'échelle de la parcelle.

Mots-clés : Nexus Eau-Énergie-Alimentation, Modèles intégrés, Multi-acteurs, Multi-niveaux, Simulations multi-agents, Prise de décision multicritère, Optimisation

Methodology for multi-actor and multi-scale decision support for Water-Food-Energy systems

This study presents a generic multi-actor multi-level methodology to optimize the management of water-energy-food nexus systems. Water-energy-food nexus systems are systems where water, energy and food resources interact and present synergies and trade-offs at varied spatial and temporal scales and whose management is impacted by cross sector decision-makers and stakeholders that take action at varied decision levels. Water-energy-food nexus systems are complex and dynamic systems for which the operational level cannot be overlooked to design adequate management strategies.

The novelty of this methodology lies in it being the first one to combine spatial operational multi-agent based integrated simulations of complete water-energy-food nexus systems with strategic multi-criteria decision-making methods and multi-objective optimization. The framework simulates nexus systems at temporal and spatial operational scales to derive strategic spatial allocations of resources. The framework is used to allocate land-use alternatives to parcels for agricultural territories. The number of possible combinations of land-use allocations to parcels equals the number of possible parcel land-use allocations explored for each parcel exponential the number of parcels in the territory considered. Multi-criteria decision-making methods based on exploratory Monte Carlo simulations have been designed to provide decision support for large territories (more than 1000 parcels) for which more than two land-use allocation alternatives are compared for each parcel. A multi-objective optimization method has been designed to produce optimized regional level land-use scenarios. The multi-objective optimization method is limited computationally and can face convergence issues when the number of possible combinations of land-use allocations to parcel explodes.

The methodology has been applied to an agricultural watershed of approximately 800 km² and 15224 parcels situated downstream the French Aveyron River. The watershed experiences water stress and is located in one of France's sunniest regions. Renewable energy production in agricultural land appears as a means to meet national renewable energy production targets and to move towards autonomous sustainable agricultural systems and regions. The installation of renewable energy generation units in agricultural land facing water stress is a perfect illustration of a complex water-energy-food system for which a holistic approach is required. MAELIA (modelling of socio-agro-ecological systems for landscape integrated assessment), a multi-agent based platform developed by French researches to simulate complex agro-hydrological systems, has been extended and used to simulate dynamics of water-energy-food nexus systems at operational level. Three strategic multi-criteria decision-making methods that combine Monte Carlo simulations with the Analytic Hierarchy Process method have been designed. The first one is local; it selects land-use alternatives that optimize multi-sector parcel level indicators. The other two are regional; decisions are based on regional indicators. The first regional decision-making method identifies the best uniform land-use regional scenario from those known and the second regional decision-making method explores the possible combinations of land-use allocations to parcels and selects the one that optimizes multi-sector criteria at regional level. A multi-objective optimization method that combines MILP (Mixed Integer Linear Programming) and goal programming has been implemented with IBM's ILOG CPLEX optimization studio to find parcel level land-use allocations that optimize regional multi-sector criteria.

Keywords: Water-Energy-Food Nexus, Integrated models, Multi-actor, Multi-level, Multi-agent based simulations, Multi-criteria decision-making, Optimization

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Abbreviations

Agri, Agrivolt: Agrivoltaics

Agro: Agriculture

AHP: Analytic Hierarchy Process

CAPEX: capital expenditures

CTP,max: PV temperature coefficient (%. $^{\circ}\text{C}^{-1}$)

DAR: Actor-Resource diagram

Dvp: under development

EF: Environmental Footprint

EPBT: Energy payback time

ETP: Evapotranspiration

GAMS: General algebraic modelling system

GHG: greenhouse gas

Gir(t): Solar irradiance at time t ($\text{W}\cdot\text{m}^{-2}$)

GIS: Geographic Information System

HO: horizon

HRU: Hydrologic Response Unit

ITK: technical itinerary

LPIS: Land Parcel Identification System

LWRF: Low-water regulating flow

MAELIA: Modeling of socio-Agro-Ecological systems for Landscape Integrated Assessment

MC: Monte Carlo

MILP: Mixed Integer Linear Programming

MINLP: Mixed Integer Nonlinear Programming

NOCT: PV Nominal Operating Cell Temperature ($^{\circ}\text{C}$)

NPV: Net Present Value

NSGA: Non-dominated Sorting Genetic Algorithm

OPEX: operating expenses

Parcel entity: tuple of parcel and meteorological polygon identifiers

P_c: PV peak power (W)

P_n: Wind turbine's nominal power (W)

PROs: organic residue products

Prot: Proteins

PSE: Process and Systems Engineering

PV: Photovoltaic

RCP: Representative Concentration Pathway

refsolcelltemp: PV reference cell temperature (°C)

RU: useful reservoir

SES: socio-ecological systems

SPV: Surface area of a PV cell (m²)

SSP: Shared Socio-economic Pathways

SWAT: Soil and Water Assessment Tool

T_{atm(t)}: Atmospheric temperature at time t (°C) .

TOPSIS: Technique for Order of Preference by Similarity to Ideal Solution

UML: Unified Modelling Language

V_{max}: Wind turbine's maximum wind speed (m.s⁻¹)

V_{min}: Wind turbine's minimum wind speed (m.s⁻¹)

V_{nom}: Wind turbine's nominal wind speed (m.s⁻¹)

V_{wind(t)}: Wind speed (m.s⁻¹)

Water indicator: Water withdrawal impact indicator

WEFN: Water Energy Food Nexus

WT: Wind Turbine

η_{mod}: PV module efficiency

Preface

Research motivation

A global energy transition is imperatively needed to reach decarbonisation objectives set by international organisations and to respect the 2015 Paris Agreement that aims at limiting global warming under 2°C with respect to preindustrial temperatures. Moreover, secure access to food and water is essential for human life and is increasingly jeopardized by climate change, urbanization and a rising population. Food, water and energy supply chains are intrinsically linked and form complex water-energy-food nexus systems at diverse spatial and temporal scales. Multiple interactions, synergies and trade-offs exist among resource. Cross-sector decision-makers intervene to manage these systems.

The scientific community works towards finding solutions that satisfy multi-actor needs and international and national objectives. Process and Systems Engineering (PSE) is a scientific engineering branch that studies and develops tools to manage and optimize physicochemical systems and related biophysical and industrial processes at varied spatial and temporal scales and decision-making levels. The PSE community has therefore its role to play in developing tools for water-energy-food nexus systems' decarbonisation.

Water-energy-food nexus systems are complex and their management requires accounting for operational conditions and uncertainties. Classical PSE tools based on mathematical modelling approaches use strategic constraints to develop optimized operational industrial processes and resource allocation schemes. However, there are two downsides to the use of these tools in the context of sustainable water-energy-food nexus systems. The first one is that they do not account for operational uncertainties related to unstable meteorological conditions that cause variable availabilities of renewable energy sources (solar and wind energy) and water. The second one is that long-term solutions found with classical PSE tools tend to prioritise activities that are economically advantageous and environmentally disadvantageous at the beginning of the simulations and thus have an important negative impact on the environment. New PSE tools where operational conditions constrain strategic solutions that satisfy multi-actor and multi-sector criteria at all simulation time steps are needed. Figure 1 below illustrates the approach shift required and taken with this PhD work.

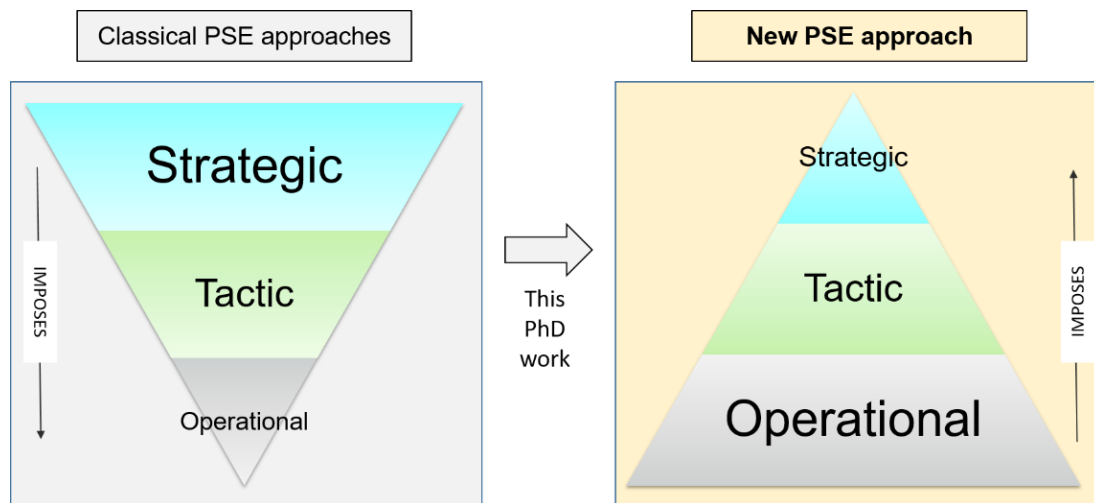


Figure 1: The shift in approach taken with this PhD work

This PhD aims at developing a methodology that matches the new PSE approach illustrated in Figure 1 above. This work addresses the need to find resource management solutions that are accepted by all actors of water-energy-food systems and that are operationally feasible.

The hosting laboratory and the national collaboration established with the INRAE

Prof. Ludovic Montastruc and Prof. Marianne Boix have directed and supervised this PhD work led in the PSE department of the Chemical Engineering Laboratory (Laboratoire de Génie Chimique (LGC) in French) in Toulouse, France, from the 1st of October 2021 to the 30th of September 2024. The thesis has been financed with a three-year public scholarship from the French Ministry of Education and Scientific Research (MESR in French).

Prof. Ludovic Montastruc and Prof. Marianne Boix had the will to investigate and explore multi-actor operational tools for water-energy-food systems following Manuel Ramos, Anastasia Roth and Daniel Pena Torres researches. (Ramos, 2016) has investigated the use of game theory multi-leader multi-follower approaches to find equilibrium strategies between actors of eco-industrial parks. The approach developed has shown promising results in terms of computational efficiency and multi-actor satisfactory rates, but the model is static, it does not account for uncertainties nor simulates renewable energy production units. (Roth, 2019) has focused on developing a holistic generic methodology to develop hybrid renewable energy parks. In (Ramos, 2016) and (Roth, 2019) it is advanced that game theory could be a promising tool to find optimised strategic resource management solutions that satisfy objectives from different actors at various decision-levels. Roth (2019)'s work has shown that future studies need to reflect on the way adaptation dynamics to territorial changes are simulated. Attention is drawn to (Jensen, 2018)'s research that states that classical PSE mathematical models are not enough to model society's complexity and human-nature interactions. Light is shed on the MAELIA platform developed by (Thérond et al., 2014) as it simulates dynamic agricultural systems as multi-agent systems where agricultural and water agents make operational and tactical decisions according to predefined strategic plans. MAELIA enables the study of

agricultural territories with a participative ComMod approach (ComMod, 2005), which involves decision-makers in all steps of scientific modelling and simulation approaches. (Peña-Torres et al., 2024) have modelled a regional water-energy-food nexus system as a multi-objective problem solved with the epsilon constraint method to develop strategic resource management policies. They have highlighted economic and environmental trade-offs. They advise the use of varied multi-sector indicators such as nutritional indicators to quantify the food resource in water-energy-food systems. They recommend the use of multi-criteria decision tools to account for different actors' preferences.

Following previous work in the laboratory and some literature research, a collaboration has been established with INRAE researchers in charge of the MAELIA platform. The aim of the collaboration being the simulation of complete agricultural water-energy-food systems with the MAELIA platform and the development of a decision-making methodology that guides decisions of installations of solar panels and wind turbines in agricultural land. More precisely, this PhD work has enabled the extension of MAELIA's agricultural water-food functionalities. It has allowed the platform to simulate the installation of renewable energy generation units in agricultural land and its impact on food and water resources. The collaboration has materialized in weekly meetings with MAELIA's developers and users, several one-to-one mail and visio exchanges between MAELIA's team and the PhD student, and some meetings between MAELIA's team and the PhD student and supervisors.

Thesis structure

Figure 2 illustrates the roadmap followed throughout this PhD work and the structure of the present manuscript. Chapter 1 includes a general introduction and shares information from an exhaustive literature review (Bois et al., 2024). The introduction describes the global environment and economic contexts that affect water-energy-food systems. It introduces water-energy-food systems and describes the Nexus approach advanced in the literature to account for both inter and transdisciplinary dimensions of nexus systems. A literature review depicts the related scientific context and research state of the art. It illustrates the need and absence of multi-level tools that produce resource management and allocation solutions constrained by operational conditions and that aim at satisfying multi-actor interests and objectives.

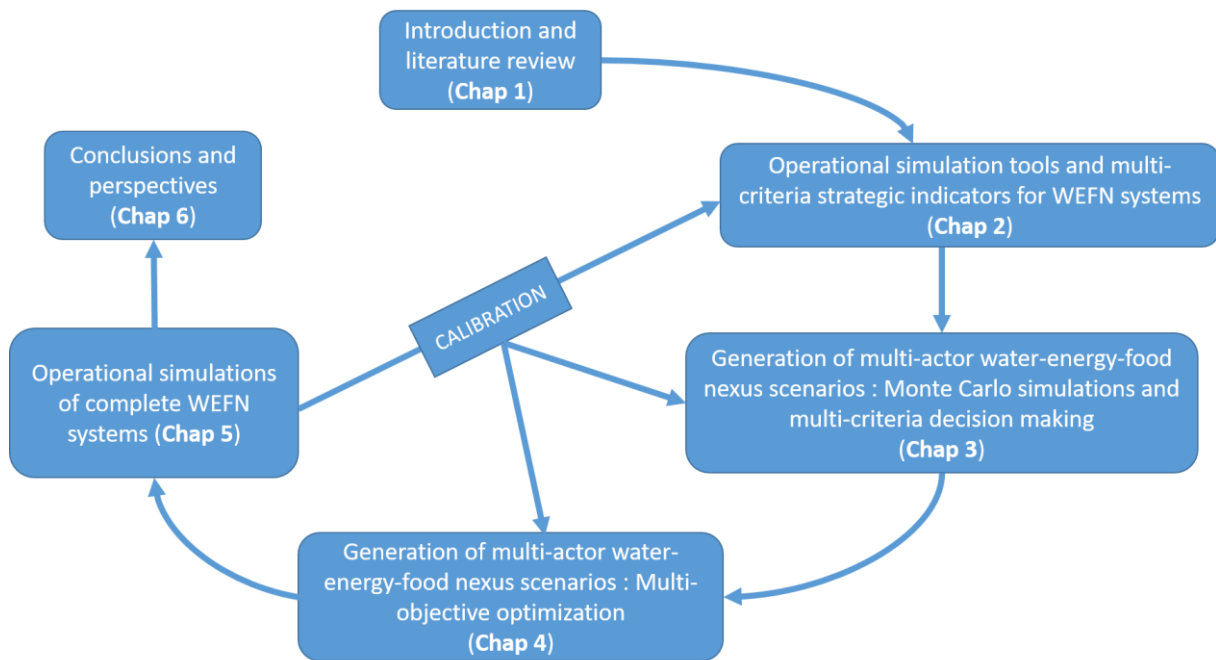


Figure 2: Thesis roadmap

Chapter 2 presents the tools selected and developed to design methodologies for water-energy-food nexus decision-making. It presents and justifies the choice of MAELIA, (modelling of socio-agro-ecological systems for landscape integrated assessment), a multi-agent based platform selected to simulate operational dynamics of water-food systems in the case study territory. It also introduces multi-criteria indicators identified and established to evaluate water-energy-food nexus scenarios and their ability to satisfy multi-sector multi-actor objectives. Lastly, it details the methodology developed to verify the suitability of agricultural land for solar panels and wind turbines. Part of chapter 2 is inspired from a congress article published in the journal of the Italian Association of Chemical Engineering on the occasion of the 2nd international conference on energy, environment and digital transition held in Palermo, Italy in October 2023 (Saint-Bois et al., 2023). Chapter 3 presents the first methodology developed to generate multi-actor multi-level water-energy-food nexus scenarios. The methodology has been illustrated in a published article ‘Multi-actor approach to manage the water-energy-food nexus at territory scale’ (Saint-Bois et al., 2024) from which the chapter is inspired. It is a decision-making methodology that combines operational multi-agent based simulations with exploratory Monte Carlo simulations and strategic multi-criteria decision-making. The methodology is conceived to find allocation scenarios of renewable energy units in agricultural land. It is demonstrated in a French case study watershed of about 15000 agricultural parcels. Chapter 4 describes the second methodology developed to generate multi-actor multi-level water-energy-food resource allocation scenarios. It also relies on multi-agent based integrated simulations to characterize nexus systems but instead of exploring and comparing scenarios it implements multi-objective optimization to produce a single optimized resource allocation scenario. Multi-objective optimization is performed with Mixed Integer Linear Programming and Goal Programming coded and solved in IBM’s ILOG

CPLEX optimization studio. Chapter 5 presents an extended version of MAELIA, which has been designed to enable operational simulations of complete water-energy-food systems. The extended version is compared with the standard version that simulates water-food systems and that was initially coupled with food and water hypotheses to characterize water-energy-food scenarios. The extended version of the platform is used to simulate scenarios produced with the two decision-making methodologies presented in the two previous chapters and to simulate expert scenarios. Chapter 6 concludes the work and draws future perspectives.

References

- Bois, A.S., Boix, M., Montastruc, L., 2024. Multi-actor integrated modeling approaches in the context of Water-Energy-Food Nexus systems: Review. *Computers & Chemical Engineering* 182, 108559. <https://doi.org/10.1016/j.compchemeng.2023.108559>
- ComMod, 2005. La modélisation comme outil d'accompagnement. *Natures Sciences Sociétés* 13, 165–168.
- Jensen, P., 2018. Pourquoi la société ne se laisse pas ... [WWW Document]. URL <https://www.seuil.com/ouvrage/pourquoi-la-societe-ne-se-laisse-pas-mettre-en-equations-pablo-jensen/9782021380101> (accessed 2.6.24).
- Peña-Torres, D., Boix, M., Montastruc, L., 2024. Multi-objective optimization and demand variation analysis on a water energy food nexus system. *Computers & Chemical Engineering* 180, 108473. <https://doi.org/10.1016/j.compchemeng.2023.108473>
- Ramos, M., 2016. Bilevel optimization of Eco-Industrial parks for the design of sustainable resource networks (phd).
- Roth, A., 2019. Développement de méthodologies génériques pour la conception optimale et durable des parcs hybrides d'énergies renouvelables (phdthesis). Institut National Polytechnique de Toulouse - INPT.
- Saint-Bois, A., Boix, M., Montastruc, L., Therond, O., 2023. Simulating Renewable Energy Production Scenarios Under Water and Food Constraints. *Chemical Engineering Transactions* 105, 457–462. <https://doi.org/10.3303/CET23105077>
- Saint-Bois, A., Boix, M., Therond, O., Montastruc, L., Villerd, J., Touche, I., 2024. Multi-actor approach to manage the water-energy-food nexus at territory scale. *Computers & Chemical Engineering* 108773. <https://doi.org/10.1016/j.compchemeng.2024.108773>
- Thérond, O., Sibertin-Blanc, C., Lardy, R., Gaudou, B., Balestrat, M., Hong, Y., Louail, T., Nguyen, V.B., Panzoli, D., Sanchez-Perez, J.-M., Sauvage, S., Taillandier, P., Vavasseur, M., Mazzega, P., 2014. Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems, in: 7. International Environmental Modelling and Software Society (iEMSs 2014), Proceedings of iEMSs 2014. San Diego, California, United States, p. 1 p.

Chapter 1: Introduction and literature review

I. Introduction

This chapter introduces the general and scientific context of the subject of study of this PhD: water-energy-food systems. It depicts the state and stress situation of existing water, energy and food resources worldwide. It outlines the global socio-economic and environmental context in which these resources evolve and the international and national initiatives taken to reach holistic integrated multi-actor management solutions. It describes the Nexus approach advocated since 2011 to account for interdisciplinary and transdisciplinary dimensions of water-energy-food systems. It presents a detailed exhaustive literature review of existing multi-actor integrated modelling approaches in the context of Water-Energy-Food Nexus systems. Finally, it recaps the main ideas exposed in chapter 1 and introduces chapter 2.

II. General context

a. Water, energy and food resources

Salt water (97.2%) and freshwater (2.8%) cover 70% of Earth's surface. Freshwater exists in the form of ice (2.15%), groundwater (0.63%), surface water (0.02%) and atmospheric water (0.001%). Groundwater is present underneath the surface and the water table, stored in the soil and rocks and forming aquifers. Surface water circulates in lakes, rivers and streams. Water is classified into blue and green water based on the speed it circulates with through the water cycle. Blue water flows slowly and refers to surface and groundwater; it accounts for 40% of precipitations. Green water flows quickly, refers to water available for plants and stored in soils and biomasses as moisture, evaporation and transpiration; it represents 60% of precipitations. Grey water refers to polluted water. Water security, at watershed scale, is characterized by sustainable access to sufficient quantities of clean water to ensure human health and ecosystem protection. The United Nations defines sustainability as a state in which "present needs are met without compromising the ability of future generations to meet theirs". Water stress equals the ratio between the annual average blue water demand in a hydrographic basin and the annual average available green water in that basin. Stress is considered negligible if this ratio is smaller than 10%, low if it is between 10 and 20%, moderate if it is between 20 and 40% and high if it is greater than 40%.

Energy is the capacity to modify a state and to do physical work such as movement or an electromagnetic radiation (light, heat...). This capacity comes from primary or secondary sources. Primary energy sources originate from natural physical or chemical phenomena, while secondary sources require a human intervention. Energy sources are classified as renewable or non-renewable depending on the time needed to generate them; if this time is short compared to human life, the resource is considered renewable and non-renewable conversely. Solar radiation, wind power, hydroelectricity, geothermal energy and biomass (wood and agricultural crops) are renewable sources. Fossil (oil, natural gas and coal) and

fissile (uranium) resources are non-renewable. Energy security is ensured when a sustainable and efficient energy supply is guaranteed.

Nutrition is the consumption of food, comprising natural products (plants, animals, microorganisms...) or processed, consumed by humans and other living beings, for nutritional and energy purposes. Food security is reached when a person has access to sufficient quantities of healthy and nutritious food, enabling it to lead a healthy and active life.

b. Global socio-economic and environmental context

Water, energy and food securities are jeopardized worldwide by increasing population, urbanization, new consumption patterns, climate change and geopolitical conflicts, which illustrate resources' unequal distribution and the critical importance of resources' thoughtful management. World population reached 8 billion in 2023 and is expected to reach 9 billion by 2037 and 10 billion by 2057. Most human activities emit significant amounts of CO₂, which lead to atmosphere, earth and oceans' warming. Global warming causes extreme phenomena such as heatwaves, snowmelt, sea level rise, ocean acidification and deforestation.

Two billion people live without secure access to clean drinking water in 2020. Humans extract water from earth to meet agricultural needs (70%), industrial needs (20%) and domestic needs (10%). Water and water management equipment are unevenly distributed on Earth: nine countries hold approximately 60% of the world's renewable freshwater resource and sanitation and irrigation techniques are very disparate among countries. Water has consequently become a major political and economic issue and studies estimate that two-thirds of the world's population could face water shortages in the coming years. Some studies advance water is not lacking, but economic and social inequalities cause water stress and deepen geographical inequalities. Eight hundred million people lacked electricity in 2021. Two-thirds of electricity produced globally originates from fossil resources, but these are depleting and unevenly distributed on Earth. It is estimated that oil will run out within 54 years, gas within 63 years, coal within 112 years and uranium within 100 years. One billion people have experienced food stress in 2020. In Southern countries, mainly in Africa, agricultural techniques remain traditional and non-mechanized. Additionally, climate variability and fluctuations in the selling prices of certain crops increase the financial instability of some producers.

Studies have shown that demands for water, energy, and food will increase in the coming years.

c. International and national initiatives

Common goals are set at international and European levels. Nations use them to develop their sustainable development plans and strategies, which draw water, energy and food territorial governance schemes. Sustainable development was defined at the Earth Summit in Rio in 1992 as being "economically efficient, socially equitable, and ecologically tenable".

➤ At international level:

The United Nations Framework Convention on Climate Change (UNFCCC), established in 1994 by 197 countries and the Paris Agreement, established in 2015 by 196 countries, have paved the way for consensus on guidelines to follow to globally slow down climate change. The UNFCCC recognized that human activities can be "dangerous" for the climate and that climate disruptions can compromise human security. It was agreed that greenhouse gas (GHG) concentrations must be kept below a level that would "dangerously" disrupt the climate. Industrialized countries are since asked to submit annual inventories of their GHG emissions. The Paris Agreement was established with the primary goal of maintaining global warming well under 2°C, preferably below 1.5°C, compared to pre-industrial temperatures (second half of the 19th century). To meet this limit, countries are encouraged to reach their peak GHG emissions as soon as possible and embark on a path of reducing GHG emissions. The 17 Sustainable Development Goals (SDGs), established by United Nations' members in 2015 as part of the United Nations 2030 Agenda for Sustainable Development, aim to inspire national and territorial guidelines. These goals account for the three—economic, social, and environmental— dimensions of sustainable development. Goals 2 ('zero hunger'), 6 ('clean water and sanitation'), and 7 ('affordable and clean energy') focus on WEFN resources.

➤ At European level:

The European Commission, in charge of the European Union's energy and climate policy, targets a greenhouse gas emissions reduction of 80 to 95% compared to 1990 levels by 2050, in order to meet the goal set by the Paris Agreement. The Commission's directives comprise an emissions trading system (EU-ETS), an 'effort sharing' policy among transportation, building and agricultural sectors and the LULUCF policy, which affects land use, land-use change and forestry. The commission requires member states to develop National Integrated Energy and Climate Plans (NECPs), in which they define national objectives and strategies to achieve them.

➤ At national level:

To meet the European Union's greenhouse gas reduction objective, France has committed to reducing its greenhouse gas emissions by one quarter, with the approval of the Law on Energy Transition for Green Growth (LTECV) in August 2015. This law introduced the French National Low Carbon Strategy (SNBC), which aims at governing energy and climate through five-year plans; named the Multiannual Energy Program (PPE). The French Ministry of Ecological Transition produces energy, climate and air scenarios to estimate to what extent international and European obligations would be met if these trend and prospective scenarios were followed, with the aim of fuelling public debate on ecological transition and decision-making in France. The reference scenario of the French energy and climate strategy for 2020 has enabled the development of the National Low Carbon Strategy (SNBC) and the Multiannual Energy Program (PPE). Main guidelines introduced in this reference scenario are achieving carbon neutrality by 2050 and producing decarbonized energy. It is noteworthy that this reference scenario is sectoral, with the state of the art drafted for each sector individually (building, agriculture, etc.).

III. The water-energy-food nexus

a. Water-energy-food systems

Water, energy and food resources interact at many spatial and temporal scales and form water-energy-food systems. Figure 1 illustrates pairwise interactions among resources.

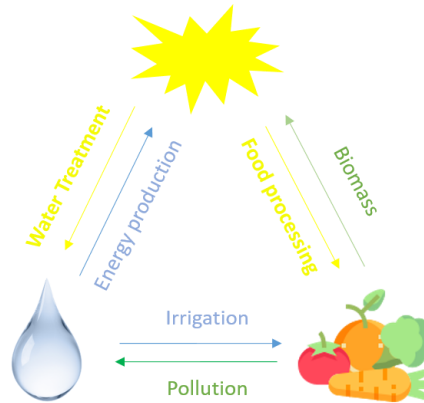


Figure 1: Water, energy and food interactions

As shown in Figure 1, water is used to grow crops through local irrigation systems and pesticides used in cropping systems pollute water. Energy is used to process food and crops can produce biomass that transforms into energy. Energy is used to treat water and water is used in energy production processes. These interactions can be local, regional or national and transboundary. For instance, energy is needed to transport local food at a national scale and gas flows through Europe to supply water and food systems. Many stakeholders and decision-makers take actions to manage these systems. Actions and decisions are made at operational, tactic and strategic levels. Operational decisions are mostly made at local level in short periods of time, tactic decisions are made at local and territorial levels for mid-term scheduling plans and strategic decisions can be made at local, territorial and larger spatial scales for longer periods of time ranging from one to several years. This makes water-energy-food systems complex systems since the state of a resource affects the state of other resources and one single sectorial action affects the entire system.

b. The Nexus approach

The Nexus approach has emerged to overcome traditional sectorial resources management. The 2011 World Economic Forum first conceived the nexus thinking to emphasize the importance of accounting for water, energy and food resources' interconnections to achieve water, energy and food securities. The German Federal Government organized the Bonn 2011 conference to contribute to the United Nations 2012 Rio Sustainable Development conference, by addressing the need of new integrated approaches that acknowledge water, energy and food interconnections and trade-offs. The German government organized an international multi-stakeholder dialogue to initiate multi-actor consultations and initiatives for water, energy and food policies development. The term Nexus has been used since the Bonn 2011 Nexus conference to refer to a holistic and systemic approach based on two axes of analysis: interdisciplinary and transdisciplinary axes. The interdisciplinary axis focuses on

synergies and trade-offs between water, energy, and food resources. The transdisciplinary axis examines the numerous system actors that intervene at different decision-making levels and their respective objectives. A holistic approach considers that a system should be studied as a unified whole and not by examining its individual components separately.

The nexus approach aims at ensuring sustainable development since it offers economic, social and environmental benefits: increased resilience to climate variability with better control over human, material, and economic risks and damages, improved energy and water efficiencies in agricultural, energy, and industrial processes, optimized agricultural land management and contribution to an international system of exchanges and innovations. The two main objectives of simulation and optimization studies around the water-energy-food nexus are the development of decision support tools to assist stakeholders in better managing resources and anticipating system evolution under different scenarios.

c. Scientific context

A search conducted filtering all publications of the Web of Science platform that contain the keywords 'water-energy-food nexus' in any field resulted in Figure 2. Figure 2 illustrates the rise of the water-energy-food nexus (WEFN) approach.

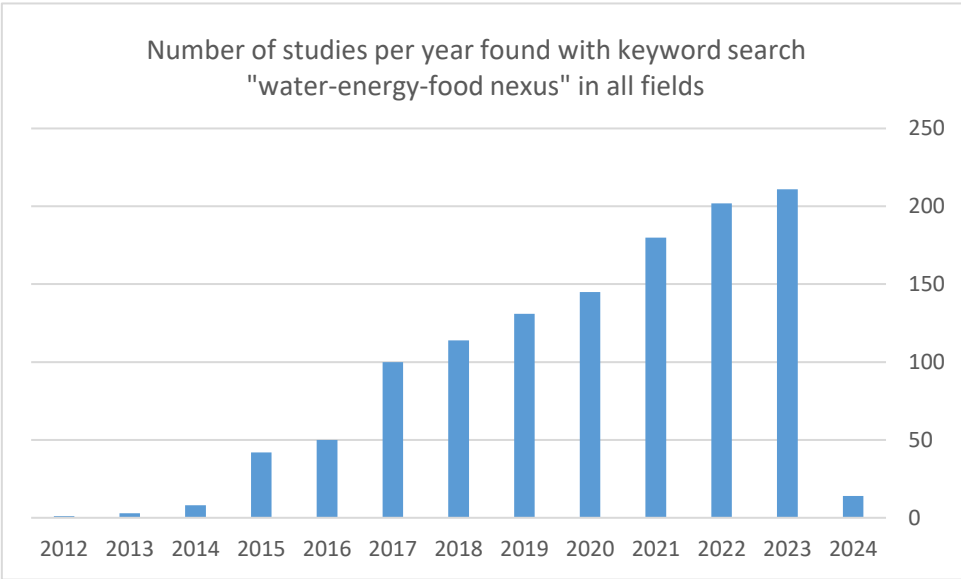


Figure 2: Rise of the WEFN approach

The same search also resulted in Figure 3. Figure 3 shows the Web of Science categories of the journals in which WEFN studies have been published. It displays research communities that address water-energy-food systems with a WEFN approach.



Figure 3: Web of Science categories of WEFN studies

Figure 3 highlights that the WEFN approach has strongly been adopted by environmental sciences and water resources communities. The involvement of the PSE community, which pertains to the engineering chemical category, is lower but necessary since PSE tools have the ability to precisely and realistically model, optimize and simulate complex systems.

Table 1 illustrates major research gaps revealed by recent WEFN reviews.

Table 1: Research gaps raised by recent WEFN reviews

Review	Research gaps
Opejin et al., (2020)	<ul style="list-style-type: none"> - Integrated modelling - Local data availability - Accounting for across scales multi decision levels governance and varied perspectives - Accounting for cross-sectoral conflicting interests - Connecting theory and practice
Stylianopoulou et al., (2020)	<ul style="list-style-type: none"> - Considering local and regional temporal and spatial scales - Integrated modelling - Connecting theory and practice
Purwanto et al., (2021)	<ul style="list-style-type: none"> - WEF security focus (ex: water quality) - Robust systems approach and datasets - Participatory stakeholder engagement - Representation of local perspectives - Context-specific policy implementation guidance
Taguta et al., (2022)	<ul style="list-style-type: none"> - Tools' transferability and scalability - Multi-scalar and local scale tools - User-inspired design and development - Geospatial capabilities

	<ul style="list-style-type: none"> - Connecting theory and practice
Sušnik and Staddon, (2022)	<ul style="list-style-type: none"> - Integrated modelling - Interdisciplinary research (ex : social sciences techniques and quantitative modelling approaches) - Multi-level stakeholder involvement - Issuing policy-relevant recommendations
Tye et al., (2022)	<ul style="list-style-type: none"> - Considering local spatial scales and local actors as active decision-makers - Participatory processes - Connecting theory and practice
Kalvani and Celico, (2023)	<ul style="list-style-type: none"> - Analyse climate change scenarios - Considering soil properties in holistic approach - Considering water quality - Considering circular economy
Segovia-Hernández et al., (2023)	<ul style="list-style-type: none"> - Insufficient interdisciplinarity - Lack of comprehensive life cycle assessment - Involving communities and stakeholders in decision-making through - Considering social and cultural contexts - Collaborating with international actors - Integrated modelling

Table 1 shows that integrated modelling and interdisciplinary research, representing local temporal and spatial scales and actors, accounting for multi-scales and decision levels governance and stakeholders' varied perspectives, multi-level stakeholder involvement and participatory processes and connecting theory and practice are the most frequent research gaps identified by recent WEFN reviews.

The PSE community excels in developing multi-objective strategic optimization tools and in applying multi-criteria decision-making methods. However, integrated operational simulation tools that consider multi-actor perspectives and objectives at varied decision-making levels are lacking. Considering this and the previously enumerated WEFN research gaps, a comprehensive review of multi-actor integrated modelling approaches in the context of WEFN systems has been conducted.

IV. Literature review: Multi-actor integrated modelling approaches in the context of Water-Energy-Food Nexus systems

a. Scope of the review

Literature advocates that proper, sustainable and resilient management of water, energy and food resources cannot be achieved if the existing interconnections between these resources are neglected (Peña-Torres et al., 2022). Since the conceptualization of the water-energy-food nexus in 2011, the scientific community has shown increasing interest in this field. WEFN has

especially been studied by environmental communities. The involvement of the Process Systems Engineering (PSE) community is recent but recommended (Peña-Torres et al., 2022). According to Garcia and You, (2016) the water-energy-food nexus is an opportunity for the PSE community to work together with experts from the environmental, behavioural and socio-political communities. Adopting a water-energy-food nexus approach is demanding due to the multi-spatial and temporal scales, multi-decision levels, multi-actors, multi-sectors and exposure to numerous climate and political uncertainties and hazards (Namany et al., 2019). PSE work has mainly focused on the mathematical optimization of industrial processes and resource allocation schemes (Di Martino et al., 2023; Medina-Santana et al., 2020; Peña-Torres et al., 2022). Game theory approaches have emerged to account for multi-actor objectives among the PSE community (Dehghan et al., 2022; Ghozatfar and Yaghoubi, 2023; Ramos et al., 2016; Wang et al., 2019). Mathematical optimization can be highly effective in modelling and analysing interactions between water, energy, and food resources (D'Amore et al., 2022). To account for the multi-actor nature of the nexus and for its uncertain nature Peña-Torres et al., (2022) recommend the use of multi-agent based modelling approaches and stochastic programming. Di Martino et al., (2023) encourage the community to investigate WEFN multi-actor decision-making processes. Gerbaud (2023) incites the PSE community to explore new modelling paradigms and to adopt participative collaborative approaches.

Namany et al., (2019), Ghodsvali et al., (2019), Magliocca (2020) and Namany et al., (2023) have addressed transdisciplinary and multi-actor nexus approaches. In a general review of nexus decision making tools for water-energy-food systems Namany et al., (2019) have emphasized the importance of developing dynamic decision models. The authors advise and justify the interest and complementarity of simultaneously using multi-agent based models, game theory and mathematical optimization. Ghodsvali et al., (2019) have reviewed transdisciplinary approaches that lead to sustainable water-energy-food nexus management. They distinguish nominal, instrumental, representative and transformative engagement according to the degree of stakeholder engagement and have found the most frequent transdisciplinary approaches are interviews, workshops, participant observation, participatory scenario development and gaming. In a review published in 2020, Magliocca (2020) has examined how agent based modelling is used to integrate human behaviour in nexus studies. He recommends the use of agent based models for WEFN to account for connections between resource producers and consumers, as well as advises the use of more behaviourally rich agents. Namany et al., (2023) have reviewed cooperative and non-cooperative game theoretic approaches applied to resource management. To the best of our knowledge, no review has focused on all multi-actor analytical approaches applied to socio-ecological water-energy-food nexus systems. The aim of this paper is to review publications that account for the multi-actor and socio-ecological natures of water-energy-food systems. Figure 4 illustrates the framework under study in this review:

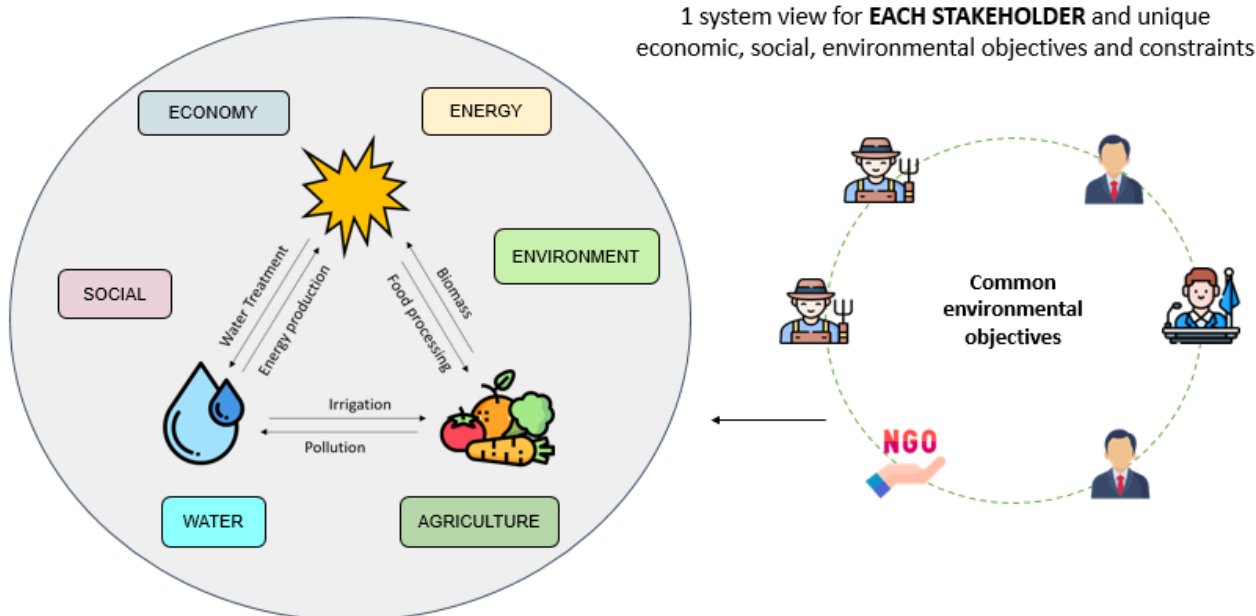


Figure 4: Multi actor view of WEF socio ecological system

Figure 4 exemplifies the multi-actor and multi-sector dimensions of water-energy-food systems, where water, energy and food resources interact through water treatment, energy and biomass production, food processing, irrigation and water pollution. These links have economic, social and environmental drivers and impacts. Farmers, enterprises, governments and non-governmental organizations with common environmental objectives, but specific system views, objectives and constraints, act and take decisions that affect the management of common water-energy-food systems. The present review aims at answering the following research questions:

1. What models account for multi-actor system views and objectives and with what aim?
2. What are the spatio-temporal scales and decisions levels addressed?
3. How are socio-ecological considerations included?
4. Are stakeholders engaged?
5. Are uncertainties addressed? And if yes, how?

b. Methodology

ScienceDirect has been used as the database for this review search since it holds papers from a wide range of disciplines. Only tools that address complete three resources nexus systems (water-energy-food nexus systems) and that quantify at least one social or environmental impact of water-energy-food nexus systems have been kept. Multi-actor economic studies on nexus systems that only consider economic constraints and objectives are out of scope. Inspired by Hachaichi and Egieya, (2023), the following search query has been applied to titles, keywords and abstracts: (“water” AND “food” AND “energy”) AND (“multi-agent” OR “ABM” OR “agent-based” OR “actor” OR “stakeholder” OR “policy-maker” OR “decision-maker” OR “game” OR “player” OR “RPG” OR “role playing game” OR “AHP” OR “analytic hierarchy process” OR “hierarchical analysis process” OR “multi-criteria” OR “coalition” OR “coordination” OR “competition” OR “collaboration” OR “resource allocation”). Sixty-two

articles fall under the scope of this literature review. These articles have been published in journals that cover the following six research areas: Environmental Studies, Energy, Water, Food, Socioeconomic Studies and Computer Science. The number of papers per research area is shown in Figure 5.

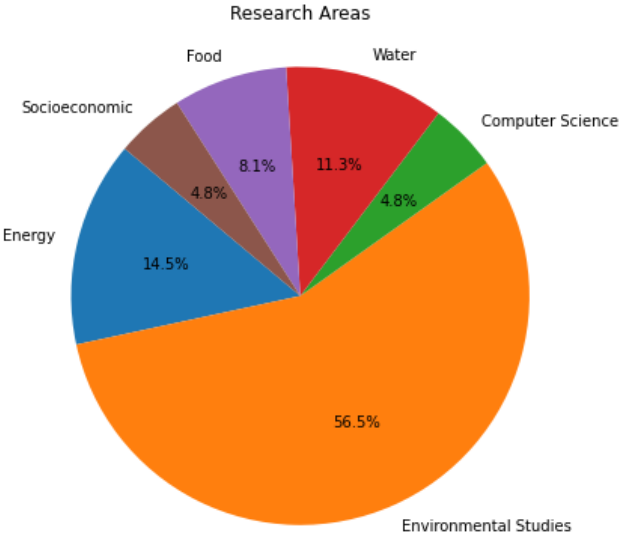


Figure 5: Research areas of the reviewed publications

Figure 5 shows that most studies are environmental studies, followed by studies published in energy and water related journals. This illustrates the lack of economic and social studies.

Three major ways have been found in the literature to account for the multi-actor and socio-ecological natures of water-energy-food systems. These are mathematical modelling, participatory approaches and multi-criteria decision-making, as illustrated in Figure 6.

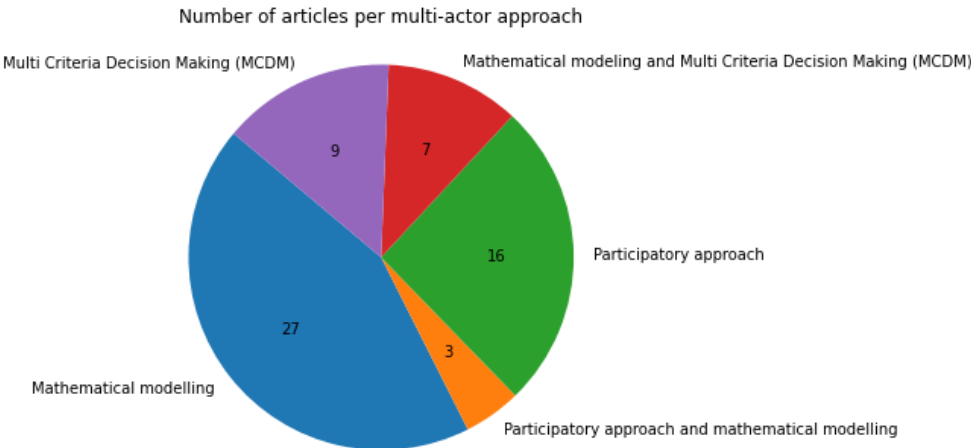


Figure 6: Studies distribution according to their multi-actor approach

Mathematical modelling describes systems with mathematical language and concepts. Mathematical modelling applied to WEFN systems encompasses agent-based models (ABMs),

multi-objective optimization (MOO), game theory and fractional programming. Participatory approaches rely on stakeholders and systems' actors to build modelling approaches. Participatory approaches applied to WEFN systems consist in qualitative social studies, workshops, serious games and digital tools. Multi-criteria decision-making (MCDM) tools evaluate systems based on multiple conflicting criteria. MCDM models applied to WEFN systems are Analytic Hierarchy Process (AHP) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) based models. Literature shows that these methods can be hybridized to obtain what we call below "mixed multi-actor approaches". Articles reviewed are classified and presented below according to the multi-actor approaches they implement.

c. Classification of multi-actor approaches for WEF socio-ecological systems

The following paragraphs analyse how each multi-actor approach answers the research questions introduced above. Attention is paid to simulated spatio-temporal scales and decision levels, as recommended by Segovia-Hernández et al., (2023). Accounting for the socio-ecological dimension is necessary to obtain sustainable resources management solutions (Segovia-Hernández et al., 2023). A method is an integrated assessment method if it accounts for the environmental dimension of the studied system (Rotmans and Van Asselt, 1996). Whether stakeholders are engaged is also looked at, as advised by Albrecht et al., (2018). If and how uncertainties and stochasticity are addressed is examined, as recommended by Peña-Torres et al., (2022).

i. Mathematical modelling

Studies under this category use mathematical models to conceptualize systems as multi-objective problems solved with mathematical and computational tools to derive strategic multi-actor resource uses. Mathematical models are also used to explore social influence and multi-actor decision-making dynamics and to study how multi-actor interactions affect systems' states.

Figure 6 shows that twenty-seven articles out of the sixty-two reviewed use mathematical modelling to account for multi-actor views and objectives on water-energy-food nexus systems. Figure 7 shows that twelve out of these studies implement multi-agent based models.

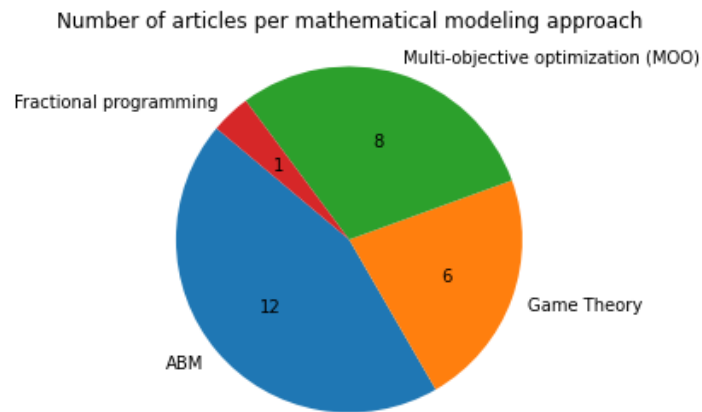


Figure 7: Studies distribution according to the mathematical modelling approach applied

Agent-based modelling is a computer-based paradigm where agents are autonomous entities that coexist in a virtual environment. Heterogeneous agents can interact between them and with the environment. Guo et al., (2020) advance agent-based models are effective for modelling and simulating operational multi-actor and multi-level systems. Table 2 illustrates how studies relying on multi-agent based models reviewed answer the previously announced research questions.

Table 2: Studies relying on multi-agent based models

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Bieber et al., (2018)	Energy Policy	Product demand data	Demographic module : 1 year, ABM : 5min District level	City-regional	15 years	Operational and strategic	The opportunity cost of food production foregone, global warming potential and economic cost are incorporated into an optimization problem run in the same framework as the ABM, on the basis of their equivalent monetary value.	No	Agents' activities are randomized

Ding et al., (2021)	Resources, Conservation and Recycling	Product demand data and explore multi-actor interaction scenarios	Ward Month	City and regional	30 years	Strategic and tactical	Resource allocations take into account hydrological state	No	Not addressed
Kaufmann et al., (2009)	Ecological Economics	Explore multi-actor interaction scenarios	Farmer	Regional	600 time-steps	Strategic	Simulates adoption of organic farming and the model reproduces the interdependence of social influence and economic factors	Yes	Agents are given a level of uncertainty towards their attitude
Haltas et al., (2017)	Energy Procedia	Explore multi-actor interaction scenarios	Hourly	National	13 years	Operational and strategic	Net energy production (biogas and electricity) from AD (and so the avoided emissions from grid energy), the mass of bio-waste processed (and avoided land-fill), and the quantum of digestate produced (as a proxy for avoided irrigation and fertilizer production) are outputs	Yes	Not addressed
Yang et al., (2019)	Journal of Hydrology	Explore multi-actor interaction scenarios	289 sub-basins Year	Transboundary basin	10 years	Strategic	Assessment of impact of dam development and climate change on baseline local HEC (hydro-ecological conditions) and NHR (natural hazard risk)	Yes	Not addressed

Abdel-Aal et al., (2020)	Journal of Cleaner Production	Explore multi-actor interaction scenarios	Daily	National	33 years	Operational and strategic	Quantifies the environmental (CO2 emissions), social (acceptability of AD plants and landfill production) and economic (costs and costs avoided) impacts of AD diffusion across GB.	Yes	Monte Carlo simulations
Bazzana et al., (2020)	Journal of Cleaner Production	Explore multi-actor interaction scenarios	Village Year	National	50 years	Multi-level strategic	The ABM considers : resources (hydrological system and natural capital), resource users, public infrastructure and public infrastructure providers.	No	Monte Carlo simulations
Bazzana et al., (2020b)	Structural Change and Economic Dynamics	Explore multi-actor interaction scenarios	Village Year	Village	60 years	Strategic	Examines impact of hydropower development on rural area's population well-being	No	Monte Carlo simulations
Bazzana et al., (2021)	Ecological Economics	Explore multi-actor interaction scenarios	Farmer, Household Year	Village	60 years	Strategic	Examines impact of eucalyptus cultivation on rural area's population well-being	No	Monte Carlo simulations
Phethet et al., (2021)	Agricultural Systems	Explore multi-actor interaction scenarios	DSSAT : Daily FEWCalc : Year	County	60 years	Strategic	FEWCalc is used to simulate agricultural and energy production and farm income based on continuation of recent ranges of crop prices, farm expenses, and crop insurance;	Yes	Not addressed

Namany et al., (2022)	Sustainable Production and Consumption	Explore multi-actor interaction scenarios	National food system actors	Month	National	4 years	Strategic and tactical	Tracking of the total costs, GHG emissions, water consumption and food losses	No	Not addressed
Elkamel et al., (2023)	Sustainable Cities and Society	Explore multi-actor interaction scenarios	1 km	1 hour	Regional	1 year	Operational and strategic	The different scenarios include different approaches to answering questions on social, economic, and environmental sustainability.	No	Not addressed

The first two articles listed in table 2 use multi-agent based models to produce resources demand data. Bieber et al., (2018) have developed the platform resilience.io, which relies on a multi-agent based model to produce operational resources demand data that serves as input for a MILP (Mixed Integer Linear Programming) optimization model that derives strategic optimized regional resource-technology networks. The optimized objectives are the opportunity cost of food production foregone (social objective), global warming potential (environmental objective) and economic cost. Uncertainties and stochasticity are incorporated in the model by randomizing agents' activities. Ding et al., (2021) have developed a multi-agent based model to produce resources demand data and explore multi-actor interaction tactical and strategic scenarios of different "what-if" WEFN management policies for systems connecting agriculture, hydroelectric generation and urban life. The multi-agent based model has been applied to simulate interactions between citizens and other institutional water uses in Cape Town, South Africa. Agents take into account the simulated hydrological state to decide upon their actions. Bazzana et al., (2020b) and Bazzana et al., (2021) explore multi-actor interaction scenarios of villages' nexus systems. Bazzana et al., (2020b) run Monte Carlo simulations to examine the impact that strategic hydropower development has on rural villages' wellbeing and Bazzana et al., (2021) run Monte Carlo simulations to examine the impact the strategic development of eucalyptus cultivation has on rural villages' wellbeing. Phetheet et al., (2021) have developed a framework that utilizes FEWCalc and DSSAT, two freeware programs, to simulate county level farmers' agricultural and energy productions and their investments constrained by water limited resources and climate change. FEWCalc is an agent based model parametrized with stakeholder data that simulates farmers' crop choices and renewable energy investments. DSSAT simulates crop production and hydrological state in arid regions. Kaufmann et al., (2009) and Elkamel et al., (2023) explore multi-actor interaction scenarios of regional nexus systems. Kaufmann et al., (2009) simulate the strategic adoption of organic farming by simulating farmers whose attributes have been parametrized with survey data from stakeholders and by making farmers interact according to social influence and economic factors. Elkamel et al., (2023) study the link between green transportation and urban agriculture to generate sustainable strategic

solutions to fight against food deserts. Seven types of agents are modelled and each of them accounts with specific empirical attributes and operational dynamic decision-making processes. Bazzana et al., (2020a), Haltas et al., (2017), Abdel-Aal et al., (2020) and Namany et al., (2022) explore multi-actor interaction scenarios of national nexus systems. Bazzana et al., (2020a)'s model on hydropower development was first applied at national scale with Ethiopian data, before being applied as mentioned earlier at village level. Haltas et al., (2017) and Abdel-Aal et al., (2020) have implemented a multi-agent based model to study the operational and strategic diffusion of anaerobic digesters (AD) in Great Britain. The model simulates operational spatially located feedstock sources, collection and transport actors, AD plants and governing actors whose behaviours are parametrized with data issued from stakeholder surveys. Abdel-Aal et al., (2020) employed Monte Carlo simulations to reproduce agents' stochastic behaviours. Yang et al., (2019) have coupled a multi-agent based model with SWAT (Soil and Water Assessment Tool) to study the impact strategic dam development has on hydrological and ecological conditions in a transboundary basin. Their model simulates water user agents whose behaviours are determined based on a stakeholder online survey. Table 2 has shown that multi-agent based models are applied to simulate nexus systems at varied spatial scales ranging from village to national scales. Contradictory agent's behaviours and wills are simulated at operational, tactical and strategic decision levels for at least one-year long periods.

Multi-objective optimization addresses problems where two or more conflicting objectives cannot be optimized without trade-offs. Solving multi-objective problems means finding the Pareto front, or in other words, Pareto-optimal solutions for which one objective cannot be optimized without deteriorating another. Table 3 shows the eight articles reviewed that implement multi-objective optimization to find solutions that satisfy conflicting objectives from different actors.

Table 3: Studies implementing multi-objective optimization

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
González-Bravo et al., (2018)	Energy Procedia	Strategic resource use optimization	1 m Year	Regional	1 year	Strategic	Minimization of GHGs and maximization of number of jobs	No	Not addressed

Nie et al., (2019)	Science of The Total Environment	Strategic resource use optimization	Production units, spatial grids Year	Experimental local station	15 years	Strategic	Minimize environmental impact	Yes	For production units with high uncertainties, a data-driven modelling method is applied to surrogate the models.
Zhou et al., (2020)	Applied Energy	Strategic resource use optimization	1 m 10 days	Water reservoir	15 years	Strategic	Maximization of average annual ratio of water supply to water demand of both public and irrigation sectors (RSD)	No	Three scenarios were specified to assess the impacts of hydrological and meteorological uncertainties on synergetic benefits of the WFE nexus
Cansino-Loeza and Ponce-Ortega, (2021)	Journal of Cleaner Production	Strategic resource use optimization	Technologies and sectors Year	Regional	1 year	Strategic	Simultaneous minimization of the costs, abstracted water and emissions	No	Not addressed
Cansino-Loeza et al., (2022)	Environmental Science & Policy	Strategic resource use optimization	Region Year	State	1 year	Strategic	Water, energy (electricity), and food demands for domestic, industrial, agriculture, and livestock activities are considered. Implementation of allocation schemes (social welfare (SW), Rawlsian (RW)),	No	Not addressed

							Rawlsian Nash (RW-N), and Nash (N)).		
Guo et al., (2022)	Journal of Hydrology	Strategic resource use optimization	Irrigation region Hydrological year	River basin	1 year	Strategic	Environmental and social objectives	No	Handle stochastic and fuzzy uncertainties from the perspective of feasibility and optimality robustness
Zuo et al., (2023)	iScience	Strategic resource use optimization	1 km Year	Regional	5 years	Strategic	Carbon sequestration maximization	No	Multi-objective interval programming with scenario analysis under Laplace criterion (MOIP-SAL)
Karamian et al., (2023)	Science of The Total Environment	Strategic resource use optimization	Crops Year	Agricultural plain	1 year	Strategic	Five social categories (participation and communication, employment, farmers' quality of life, food security, and desirability of working conditions for each crop) were designed in the form of thirteen	Yes	Not addressed

							variables to obtain the social dimension objective		
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Table 3 illustrates that all multi-objective optimization problems are solved to find optimized strategic resource use solutions. Nie et al., (2019), Zhou et al., (2020) and Karamian et al., (2023) have modeled multi-objective problems to develop local strategic resource allocation schemes. Nie et al., (2019) implement a MINLP (Mixed Integer Non Linear Programming) problem designed with stakeholders in GAMS to optimize economic profit, food yield, energy use, water use and environmental penalty of land in an experimental station located in Yucheng County, Shandong Province of China. Surrogate data driven models are parametrized to simulate uncertain crop and livestock production. Zhou et al., (2020) have used a MOGOA (multi-objective grasshopper optimization algorithm) to optimize renewable power generation from a water reservoir mixing floating photovoltaic and hydropower generation and satisfaction of water and food demands. MOGOA maximizes power production, the average annual ratio of water storage to reservoir capacity and the average annual ratio of water supply to water demand of both public and irrigation sectors. Three hydrological and meteorological scenarios are simulated to address uncertainties. Karamian et al., (2023) have used compromise programming (CP) to solve a MOGA (multi-objective genetic algorithm) that maximizes WEFNI (an indicator of resource state) and a social dimension indicator and minimizes a life cycle indicator that accounts for environmental impacts. The social dimension objective was built upon farmers’ interviews. Guo et al., (2022) have developed a distributed multi-objective uncertain optimization model that combines robust stochastic programming, robust possibilistic programming and multi-objective programming to design strategic solutions under uncertain conditions for irrigated agriculture development in a river basin. Optimized objectives are net agricultural economic benefits, water consumption, CO2 emissions, a matching coefficient of allocated water and land resources that measures equity of spatial allocations, and an ecological system service value. González-Bravo et al., (2018), Cansino-Loeza and Ponce-Ortega, (2021), Cansino-Loeza et al., (2022) and Zuo et al., (2023) have applied multi-objective optimization to derive optimized strategic structures of regional and national nexus systems. González-Bravo et al., (2018), Cansino-Loeza and Ponce-Ortega, (2021) and Cansino-Loeza et al., (2022) have all modelled MILP problems solved with different GAMS solvers. González-Bravo et al., (2018) aim to maximize gross annual profit, minimize GHGs emissions and maximize the number of jobs generated by water and power distribution grids built for food production in the Sonora desert in Mexico. Cansino-Loeza and Ponce-Ortega, (2021) optimize the location and selection of water, energy and food technologies in

the Lagunera Region in Mexico. The model minimizes economic costs, abstracted water and GHGs emissions simultaneously. Cansino-Loeza et al., (2022) maximize a water-energy-food security index that measures the availability, accessibility and sufficiency of resources under different social and economic allocation schemes to obtain solutions that satisfy different multi-stakeholder structures. Zuo et al., (2023) have developed a multi-objective interval programming model to analyse uncertain scenarios of crop planting that balance system economic benefit and net carbon sequestration, as a measure of the state of ecosystem services. Laplace criterion is used to assume the probability of each scenario is equal. Table 3 has shown that multi-objective optimization, as multi-agent based models, is also applied to nexus systems existing at varied spatial scales. However, multi-objective optimization designs nexus systems according to strategic multi-stakeholder confronting views, whereas multi-agent based models are used to explore interaction scenarios of actors acting operationally, tactically and strategically.

Game theory is an applied mathematics computer science that enables modelling strategic decision-making processes among interdependent cooperative or competitive stakeholders (Rasmusen, 2006). Table 4 shows the six articles reviewed that use game theory to find solutions that satisfy conflicting objectives from different actors.

Table 4: Studies relying on Game Theory

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Uslu et al., (2021)	Knowledge-Based Systems	Study social influence	Actors Rounds of collective decision making processes	Regional	20 rounds of decision-making	Strategic	Actors select solutions as a trade-off between their economic profit and environmental protection that represents the risk in the system.	No	Trust uncertainties: The proposed solutions are based on the estimation of the rating characteristics, that is strategy in game theory, of other actors.
Ma et al., (2021)	Journal of Cleaner Production	Strategic resource use optimization	Sea basin 5 years	Transboundary basin	15 years	Strategic	Environmental and economic objectives	Yes	Chance constrained programming.
Zhang et al., (2021)	Journal of Cleaner Production	Strategic resource use optimization	Irrigation district Month	River basin	1 year	Strategic	Available nature resources, including land and water resources, are considered as	No	Randomness of surface runoff is considered through bi-level

							constraints. GINI coefficient of economic income is a lower-level objective.		multi-objective stochastic programming (BLMOSP)
Tan et al., (2021)	Journal of Cleaner Production	Strategic resource use optimization	POBC process units Hour	Palm oil based complex	Indefinite	Strategic	Environmental and economic objectives	No	Fuzzy optimization approach
Wang et al., (2023)	Journal of Hydrology: Regional Studies	Strategic resource use optimization	Dams Daily	Transboundary basin	19 years	Strategic	CWatM model integrates hydrological modules and domestic, agricultural, industrial and livestock water demand modules to simulate runoff and water withdrawals accurately	No	Not addressed
Emamjomehzadeh et al., (2023)	Journal of Environmental Management	Simulate agent's decision making processes	Basin Year	River basin	25 years	Strategic	Urban metabolism models water, energy, food and GHG flows	No	A Genetic Algorithm is used to approximate uncertain parameters of the urban metabolism model

From the six studies above, four address national or transboundary river basins, one addresses a regional nexus system and one deals with a palm oil based complex. Uslu et al., (2021) have developed a hybrid human-machine iterative framework that studies social influence and the impact trust sensitivity has on strategic decision-making on resource allocation schemes at regional level. Actors propose solutions that optimize a weighted average between the resource share they receive and the trust the community has on them, which illustrates the solution's degree of environmental friendliness. Ma et al., (2021) have implemented a bi-level decentralized chance-constrained programming (BDCP) model to derive synergetic management solutions of resources in the transboundary Aral Sea Basin under uncertain conditions. The bi-level model takes the form of a Stackelberg game where the upper-level player aims to maximize system benefit and the lower level player aims to maximize food production, ecological water allocation, and electricity generation. Experts have been consulted to get and validate the model's input data. F. Zhang et al., (2021) have also developed a bi-level model to find strategic agricultural water and land management solutions that satisfy regional water managers and farmers in China's Heihe River Basin and that reduce the system's carbon emissions. The bi-level model is implemented as a multi-objective

stochastic program that accounts for surface runoff uncertainties. The regional water managers' objectives are carbon footprint minimization and system total profit and irrigation water productivity maximization. Farmers' objectives are minimization of GINI coefficient of economic incomes (to balance economic benefits among farmers) and maximization of total net economic benefit and crop yield. J. Wang et al., (2023) have developed a discontinuous nonlinear program to model transboundary cooperation in the Brahmaputra River Basin. The model optimizes agricultural, hydropower and fishery production and reallocates incremental benefits among stakeholders from different countries using two benefit reallocation methods: Nucleolus and Nash-Harsanyi bargaining method. CWatM, a hydrological model, is used to simulate water demands, withdrawals and runoff. Emamjomehzadeh et al., (2023) combine urban metabolism and reinforcement learning to derive strategic resource management solutions for Iran's Salt Lake basin. The urban metabolism model simulates water, energy, food and GHGs flows and Q-learning is used to simulate agent's decision making processes. Uncertain parameters of the metabolism model are approximated with a genetic algorithm. Tan et al., (2021) have coupled fuzzy optimization approach and a cooperative game model developed by Maali, (2009), based on linear programming, to optimize resources management in a palm oil based complex and optimally allocate benefits and impacts among processes of the palm oil based complex. The above has shown that game theory is employed for multi-actor strategic settings to study social influence, solve competitive and coordinative management scenarios and model learning behaviours.

Fractional programming optimizes a ratio function in which the numerator and the denominator are conflicting objectives. Table 5 shows the main features of the only article reviewed that applies fractional programming to find solutions that satisfy conflicting objectives from different actors.

Table 5: Studies relying on Fractional Programming

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Huang et al., (2022)	Journal of Contaminant Hydrology	Strategic resource use optimization	Crops Year	Regional	6 years	Strategic	Optimizes economic benefit subject to water use minimization	No	IFP deals with uncertainties expressed as interval parameters

Huang et al., (2022) have developed an inexact fractional programming method to derive strategic agricultural water management solutions in Henan Province, China, under uncertainties. The model balances economic profit maximization and water use minimization. It maximizes unit benefit defined as the ratio of agricultural profit per water consumption (\$/m³). Uncertainties are expressed as interval parameters.

ii. Participatory approaches

Studies under this category rely on participatory approaches to conceptualize system models following multi-actor discussions and interaction analyses with the aim to understand how multi-actor interactions and power dynamics affect resources management and system state and to engage system stakeholders and transfer scientific knowledge to global citizens.

Figure 6 shows that sixteen articles out of the sixty-two reviewed use participatory approaches to account for multi-actor views and objectives on water-energy-food nexus systems. Figure 8 illustrates that participatory approaches that implement social analysis techniques are the most frequent (seven out of sixteen articles), followed by workshops and frameworks that mix more than one participatory method.



Figure 8: Studies distribution according to the participatory approach applied

Social analysis techniques are qualitative tools that use diagrams, networks, graphs and frameworks to conceptualize multi-actor interactions. Table 6 summarizes the main features of the seven studies that apply social analysis techniques to account for multi-actor interactions.

Table 6: Studies relying on Social Analysis techniques

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Stein et al., (2018)	Environmental Science & Policy	Identify influential actors	Regional	Regional	Atemporal	Strategic	Connections between actors of environment, water, energy and food sectors are studied	Yes	Not addressed

Franz et al., (2018)	Environmental Science & Policy	Conceptualize multi-actor connections	Regional Atemporal	Regional	Atemporal	Strategic	Environmental impacts of actor networks and WEFN systems are represented	Yes	Risk is included as a new analytical category of the GPN (Global Production Network) approach.
Märker et al., (2018)	Renewable and Sustainable Energy Reviews	Conceptualize multi-actor connections	National Atemporal	National	Atemporal	Strategic	IAD framework analyzes collective choice processes and social interactions within SES. MTF analyzes complex resource governance systems – namely water systems – and trace their emergence.	Yes	New links are built across sectors to deal with the uncertainty arising from integrating a range of sectors and stakeholders.
Pahl-Wostl, (2019)	Environmental Science & Policy	Conceptualize multi-actor connections	Regional Atemporal	Regional	Atemporal	Strategic	WEF nexus interactions and governance deficits are captured by analysing actor-ES (ecosystem) networks	No	Not addressed
Bahri, (2020)	Science of The Total Environment	Conceptualize multi-actor connections	Reservoir Atemporal	Reservoir	Atemporal	Strategic	CLD represents links between system actors and the environment	Yes	Not addressed
Zhang et al., (2021)	Resources, Conservation and Recycling	Conceptualize multi-actor	City Atemporal	City	Atemporal	Strategic	CLD represents links between system	Yes	Not addressed

		connections					actors and the environment		
Alasam Alzaabi and Mezher, (2021)	Renewable and Sustainable Energy Reviews	Identify influential actors	National Atemporal	National	Atemporal	Strategic	Analysed policies are environment friendly	Yes	Not addressed

Bahri, (2020) and T. Zhang et al., (2021) use causal loop diagrams (CLDs) to analyse relationships between actors of WEFN systems that make decisions that affect local ecosystems and to find sustainable strategic resource management solutions. Bahri, (2020) have used CLDs to qualitatively illustrate system dynamics of system archetypes of the multi-actor water-energy-food systems existing in Jatiluhur reservoir, Indonesia. System archetypes refer to well-known scenarios such as Limits to growth or Success to Successful scenarios. Agricultural, industrial and residential actors are represented in the system archetypes and they have been consulted to gather the necessary knowledge to build the CLDs. T. Zhang et al., (2021) have used CLDs to identify sustainable multi-actor strategic resource management scenarios of the City of Bayan Nur situated in Hetao Irrigation District (HID), west of the Inner Mongolia Autonomous Region. Stakeholders have been engaged in the design phase of several CLDs that have been merged and reduced to obtain a general system CLD. Stein et al., (2018) and Alasam Alzaabi and Mezher, (2021) rely on social network analysis to identify powerful actors. Stein et al., (2018) have studied embeddedness of the multi-stakeholders governing water, energy and food resources in Tana and Upper Beles sub-basins, located in the upstream of the Blue Nile river basin, Ethiopia. They have translated strategic positional, relational and structural embeddedness into centrality, cohesion and position concepts from social network analysis. This enables them to identify powerful actors together with constraints and cooperation opportunities. Actors have been surveyed to build knowledge to construct the social networks. Alasam Alzaabi and Mezher, (2021) use social network analysis to identify national influential actors of water-energy-food nexus systems' governance. Experts were interviewed to decide on the stakeholders represented by the social networks. Pahl-Wostl, (2019) analyses actor – ecosystem (ES) networks to identify cooperation and coordination opportunities between actors of water-energy-food nexus systems. Franz et al., (2018) and Märker et al., (2018) use frameworks to analyse multi-actor connections and the associated environmental impacts. Franz et al., (2018) expand the Global Production Network (GPN) framework to understand strategic dependencies between actors of water-energy-food nexus based products that integrate into a regional agro-food cluster. They expand the GPN framework by adding a risk analytical category to analyse how multi-actor connections change under risk scenarios. GPN illustrates environmental impacts associated to actors' actions. Märker et al., (2018) have developed a MTF-based IAD framework to guide multi-actor institutional changes of national water-energy-food nexus related strategies. The management transition framework (MTF) was developed to analyse water governance systems and the Institutional Analysis Framework (IAD) was developed to analyse decision-making processes and social interactions of Socio Ecological Systems (SES). Combined they enable horizontal and vertical integration of institutions to design multi-actor sustainable

strategic WEFN policies. Table 6 has shown that social analysis techniques enable the conceptualization of multi-actor strategic interactions for socio-ecological systems existing at varied spatial scales and the identification of influential actors.

Workshops are group meetings usually coordinated by one or more people held to collectively build knowledge through organized discussions and/or exercises. Table 7 summarizes the main features of the three studies that rely on workshops to gather and build WEFN multi-actor knowledge.

Table 7: Studies relying on Workshops

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Almulla et al., (2022)	Energy for Sustainable Development	Problem, scenarios and evaluation metrics definition	m Year	River basin	30 years	Strategic	WEAP (Water and Agriculture model)	Yes	Uncertainty-Impact matrix
Tilt et al., (2022)	Environmental Science & Policy	Scenarios and conceptual model definition	km Year	Regional	5 - 10 years	Strategic	The structural framework considers the state of water, energy, land and ecological resources	Yes	Plausible future scenarios are developed around the most important and/or uncertain drivers of change
Naranjo et al., (2023)	Journal of Cleaner Production	Scenarios definition	ha, Crops Year	Sub river basin	5 years	Strategic	WEAP (Water and Agriculture model), lifecycle environmental assessment and socioeconomic analysis modules	Yes	Not addressed

Workshops can be held to collectively design multi-actor scenarios, such as Naranjo et al., (2023) do, to identify the problem at hand, to build scenarios and indicators, such as Almulla et al., (2022) do, or to collectively build scenarios and design a conceptual system model, such as Tilt et al., (2022) do.

Serious games are games designed to combine educational and entertaining objectives. They aim to be pleasant and easy to play with, while transferring and conveying knowledge simultaneously. Stakeholders of the systems modelled by the games play the game either

through group playing sessions that take place in a physical room or through online game interfaces. Table 8 illustrates the main characteristics of the Nexus Game.

Table 8: Studies relying on Serious Game

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Mochizuki et al., (2021)	Global Environmental Change	Ease stakeholder engagement	Energy and water related facilities Rounds of decision-making and reflection phases Year	Transboundary basin	Indefinite	Strategic	Roles (enacted by players during the gameplay) affect the game environment that contains biophysical elements (such as rivers or land), physical infrastructure (e.g. dams), as well as economic and social relationships (e.g. transformation of resources into revenue streams).	Yes	Not addressed

Mochizuki et al., (2021) have designed the board Nexus Game to facilitate communication and collaboration between stakeholders of the transboundary Kariba dam situated between Zambia and Zimbabwe. The board game simulates physical infrastructures such as dams and ecosystem services and impacts such as water flow and water pollution. Players engage in four rounds of collective decision-making and reflection phases during which strategic investment decisions and resource allocation schemes are discussed.

Some studies mix more than one of the participatory approaches reviewed so far. These studies are presented in Table 9.

Table 9: Studies relying on mixed participatory approaches

Paper reference	Journal	Methods	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
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Purwanto et al., (2019)	Journal of Cleaner Production	Social analysis and workshops	Conceptualize multi-actor connections, conceptual model definition	Sub-sectors/ Regional Atemporal	Regional	Atemporal	Strategic	Population, economic and ecosystem services were considered as exogenous drivers of the system	Yes	Not addressed
Anejonu et al., (2020)	Biomass and Bioenergy	Digital tool and workshops	Problem, scenarios and evaluation metrics definition, stakeholder engagement	ha Year	Watershed	10 years	Strategic	The digital tool assesses environmental and socioeconomic impacts of advanced biofuel refineries. This study combined the Ecosystem Services (ES) framework with the supply chain assessment to define the boundaries of the biofuel system.	Yes	Not addressed
Sušnik et al., (2021)	Science of The Total Environment	Workshops, social analysis and serious game	Scenarios and conceptual model definition, conceptualize multi-actor connections	Sub-regions Month	National	50 years	Strategic	Simulated policies address a number of pertinent environmental concerns	Yes	Not addressed

			ons and ease stakeholder engagement					in Latvia, including reducing nitrogen (N) runoff to waterbodies, reducing energy consumption for heating and increasing the share from biomass sources, increasing the share of electricity from wind production, and reducing GHG emissions.		
Alletto et al., (2022)	Agricultural Systems	Workshops and serious game	System design and ease stakeholder engagement	Farm Month / Year	Local	8 years	Strategic and tactical	Economic, environmental and social indicators.	Yes	Not addressed
Balaican et al., (2023)	Environmental Science & Policy	Digital tool and workshops	Problem definition and stakeholder engagement	City Month	City	1 year	Strategic and tactical	The Tulcea tool connects consumers with small local producers, allowing them to promote their products and locations, thus increasing the resilience of the local	Yes	Not addressed

									food system. The consumer profile form collects annual energy and water use, including wastewater.	
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Purwanto et al., (2019) combine workshops and social analysis by mixing group model building (GMB) and causal loop diagrams (CLD) to develop a multi-actor strategic model of the water-energy-food security in Karawang Regency region, Indonesia. Agriculture, industry and population appear as actors of the mapping built and economic and ecosystem services appear as exogenous drivers. Anejionu et al., (2020) and Balaican et al., (2023) mix workshops and digital tools to engage stakeholders and ease learning and participatory knowledge building on multi-actor WEFN systems. Balaican et al., (2023) designed the Tulcea tool, a mobile friendly online tool designed with local stakeholders to connect them among them. The tool enables coordination and cooperation between small local food producers and consumers, promoting local consumption. The tool informs about annual energy and water consumption of food products and monthly evolution of vegetable sales. It can therefore serve as a strategic and tactical decision tool for consumers. Anejionu et al., (2020) have developed Ecometrica, a geospatial reporting tool applied to a watershed in Sardinia, Italy. The tool has been built with stakeholders and addresses spatial environmental and socioeconomic impacts of advanced biofuel production projects. Scenarios and indicators have been identified with multiple water-energy-food stakeholders. The selected indicators quantify environmental and ecosystem impacts such as GHGs emissions, impacts on water resources and biodiversity, resources production (energy, food and animal feed) and employment and income generation rates. Alletto et al., (2022) used a prototype version of the “Mission Ecophyt'eau®” serious game to ease and organize communication between farmers, agricultural advisers and scientists to develop strategic and tactical crop diversification scenarios for an 8-year period farm experiment in South-Western France. The performance of the cropping systems developed is evaluated with multi-criteria economic, environmental and social assessment. Sušnik et al., (2021) have mixed workshops, social analysis and the development of a SIM4NEXUS based serious game to promote collective building of scenarios, collective design of a system dynamic model, and ease stakeholder engagement to simulate environmental friendly policies over a 50-year period for the water-energy-food-land-climate nexus in Latvia. Table 9 has shown that mixed participatory approaches enable multi-actor modelling of nexus systems existing at varied spatial scales. They ease the development of multi-actor and multi-sector strategic and tactical policies and trajectories.

iii. Multi-criteria decision-making

Studies under this category use multi-criteria decision-making techniques that leverage data collected on nexus systems' states to compute values of multiple indicators that render an idea of systems' states. Multi-criteria decision making techniques combine and weight indicators in different ways and with the help of stakeholders and stakeholders' knowledge to evaluate resource management scenarios in a multi-actor integrative manner.

Figure 9 shows that nine articles out of the sixty-two reviewed use MCDM approaches to account for multi-actor views and objectives on water-energy-food nexus systems. Figure 9 illustrates that MCDM approaches that implement analytical hierarchy process (AHP) are the most frequent (seven out of nine articles).

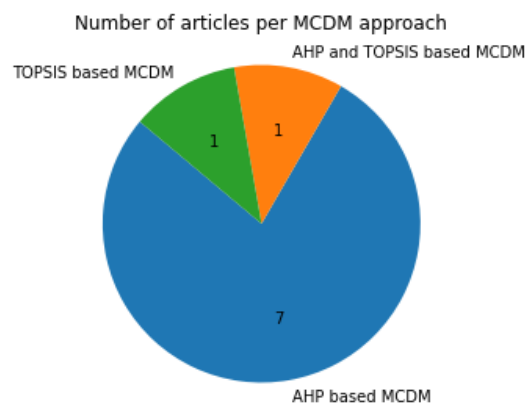


Figure 9: Studies distribution according to the MCDM approach applied

Analytic Hierarchy Process (AHP) is a multi-criteria decision-making structured technique used to compare alternatives with respect to a goal by using evaluation criteria. The weights of each criteria are determined with an input pairwise comparison matrix that contains relative pairwise criteria's importances given by stakeholders. Table 10 summarizes the main features of the seven studies that rely on AHP to evaluate solutions with a multi-actor perspective.

Table 10: Studies relying on AHP based approaches

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Nhamo et al., (2020)	Environmental Science & Policy	Integrated multi-actor assessment	Country Year	National	1 year	Strategic	Considers economic, social and environmental indicators	Yes	Expert engagement and data analysis
Namany et al., (2021)	Sustainable Cities and Society	Integrated multi-actor assessment	Country Year	National	1 year	Strategic	Considers economic, social and environmental indicators	Yes	Not addressed

Shu et al., (2021)	Environmental and Sustainability Indicators	Integrated multi-actor assessment	Household Year	National	1 year	Strategic	Considers resources availability indicators and household resources' accessibilities	Yes	Not addressed
Yuan et al., (2021)	Science of The Total Environment	Integrated multi-actor assessment	City Year	City	1 year	Strategic	Considers economic, social and environmental indicators	Yes	Not addressed
Viccaro et al., (2022)	Renewable Energy	Integrated multi-actor assessment	100 m Month	Regional	1 year	Strategic	Water, energy and land footprint indicators and land suitability and nexus sustainability analysis	Yes	Fuzzy logic technique
Wang et al., (2023)	Ecological Indicators	Integrated multi-actor assessment	City Year	River basin	9 years	Strategic	Considers economic, social and environmental indicators	Yes	Entropy weighting
Cheng et al., (2023)	Sustainable Production and Consumption	Integrated multi-actor assessment	National Year	National	10 years	Strategic	Considers economic, social and environmental indicators	Yes	Entropy weighting

Four out of the seven studies have applied AHP to find national solutions that satisfy best multi-actor objectives. Nhamo et al., (2020) have used AHP to assess South Africa's multi-criteria progress towards achieving WEFN resources security and to identify areas and sectors that need priority interventions. They state that uncertainties are dealt with by mixing expert engagement and empirical data analysis to establish the pairwise criteria comparison matrix. Namany et al., (2021) have used AHP to evaluate the performance of national's policies towards achieving nexus sustainability, security and resilience. Shu et al., (2021) have used an AHP with national and household resource availability indicators to estimate UK's WEFN resilience in years 1990, 2000 and 2010. Cheng et al., (2023) use AHP and the entropy method to evaluate the evolution of resources coordinated development level and security in China through years 2010 to 2020. The same model was applied at river basin level to the Yellow River basin in Shandong Province, China by S. Wang et al., (2023). Viccaro et al., (2022) have applied AHP to obtain criteria weights to apply GIS (Geographic Information System) based Ordered Weighted Averaging (OWA) technique to evaluate land suitability for biofuels in the Basilicata region, Italy. Fuzzy logic is used to deal with data uncertainties. Yuan et al., (2021) have applied AHP to evaluate the current sustainability level of four cities: Amsterdam, Eindhoven, Taipei, and Tainan. Three strategies to achieve sustainability are compared with

the AHP: infrastructure development, technological innovation, and partnership collaboration.

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is also a multi-criteria decision making method that finds the best solution from a set of solutions by measuring geometric distances based on a set of criteria between candidate solutions and the ideal and worst solutions. The ideal solution corresponds to the solution with criteria values at their best and the worst solution corresponds to the solution with the criteria values at their worst. Table 11 summarizes the main features of the only article found that applies TOPSIS.

Table 11: Studies relying on TOPSIS based approaches

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Valencia et al., (2022)	Resources, Conservation and Recycling	Integrated multi-actor assessment	m2 Daily	Regional	10 years	Strategic	Considers economic, social and environmental indicators	No	Not addressed

Valencia et al., (2022) used TOPSIS to select the best transition scenario among four sustainability scenarios to achieve carbon neutrality and circular economy in the urban region of Orlando, Florida.

Features from the only water-energy-food nexus study found that applies both AHP and TOPSIS are shown in Table 12.

Table 12: Studies relying on AHP and TOPSIS based approaches

Paper reference	Journal	Goal	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Gu et al., (2022)	Agricultural Water Management	Integrated multi-actor assessment	Province Year	River basin	9 years	Strategic	Considers economic, social and environmental indicators	Yes	Type-2 fuzzy sets

Gu et al., (2022) developed a framework that combines the use of a Pressure-State-Response (PSR) model, type-2 fuzzy sets, AHP, TOPSIS and Combinative Distance-based Assessment (CODAS) to evaluate the evolution of the WEFN security in the Yellow River basin, China from year 2006 to year 2019. The PSR model is used to build a WEFN security index based on pressure, state and response indicators. Type-2 fuzzy sets and AHP are combined to compute weights for pressure, state and response criteria under uncertain conditions. The use of TOPSIS and CODAS, two multi-criteria decision-making techniques, is compared to evaluate the regional nexus security based on the results from the previous framework steps.

Studies in this section have shown that MCDM techniques such as AHP and TOPSIS are used to find weights for multi-criteria analysis techniques and to determine best strategies to achieve a certain goal with respect to multi-actor and multi-sector criteria. These techniques are used at varied spatial scales to evaluate yearly performances of strategies.

iv. Mixed approaches

Some studies combine the multi-actor approaches presented above. Figure 10 presents the distribution of studies per combination of multi-actor approaches. Seven studies combine mathematical modelling and MCDM and three studies combine participatory approaches with mathematical modelling.

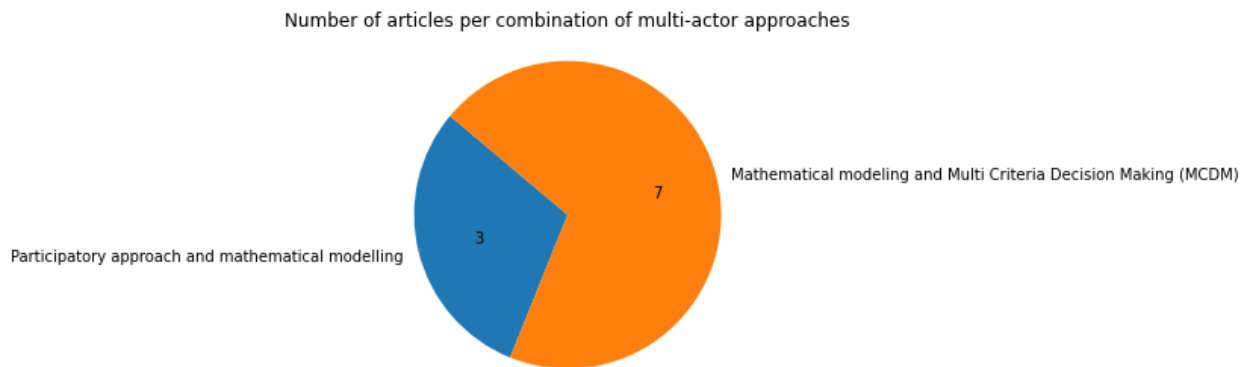


Figure 10: Studies distribution according to the combination of multi-actor approaches

Table 13 gives key information on the seven studies that combine mathematical modelling with MCDM.

Table 13: Studies that combine mathematical modelling and MCDM

Paper reference	Journal	Methods	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Falconer et al., (2020)	Journal of Cleaner Production	ABM and TOPSIS based MCDM	km Daily	County	17 years	Operational and strategic	Economic, environmental and social indicators	Yes	Monte Carlo simulations
Radmehr et al., (2021)	Agricultural Water Management	MOO and TOPSIS based MCDM	Rural district Month	River basin	1 year	Strategic	Economic and environment indicators	Yes	Not addressed
Li et al., (2021)	Agricultural Systems	MOO and AHP based MCDM	Region Crop life cycle	Province	Crop life cycle	Strategic	Trade-offs among water and energy utilization efficiency, economic benefits and environment	No	Not addressed

							ntal protection		
Yue and Guo, (2021)	Agricultural Water Management	MOO and AHP based MCDM	Irrigation subareas Rice growth stages	Irrigation district	1 year	Strategic	Economic and environmental objectives	No	Stochastic multi-objective programming, triangular fuzzy numbers, fuzzy credibility-constrained programming
Yue et al., (2021)	Resources, Conservation and Recycling	MOO and AHP based MCDM	Irrigation subareas Crop growth stages	Irrigation district	1 year	Strategic	Efficiency-equity trade-off in water and land resources allocation	No	Stochastic multi-objective programming and triangular intuitionistic fuzzy sets
Yue et al., (2022)	Agricultural Systems	MOO and AHP based MCDM	Irrigation subareas Crop growth stages	Irrigation district	1 year	Strategic	Economic, environmental and social indicators	No	Stochastic multi-objective programming, triangular fuzzy numbers, fuzzy credibility-constrained programming
Sun et al., (2022)	Journal of Cleaner Production	Game Theory and TOPSIS based MCDM	Region Year	Regional	19 years	Strategic	Economic, environmental and social indicators	Yes	Not addressed

Falconer et al., (2020) combine ABM and TOPSIS based MCDM to explore and compare anaerobic digestion (AD) development strategies in Lincolnshire, a county in east central England. They have prototyped a decision support tool that uses ABM to simulate operational multi-actor interactions and TOPSIS to rank AD strategic development policies according to economic, environmental and social indicators. Monte Carlo simulations are run to deal with uncertain ABM parameters. Five studies mix MOO with a MCDM tool. Radmehr et al., (2021) combine MOO with TOPSIS to optimize resources use and lead a multi-actor integrated assessment of the WEFN in Neishaboor basin, Iran. A nonlinear program is solved with the epsilon constraint method and CONOPT 4 solver in GAMS to find solutions that minimize environmental damages and maximize groundwater use benefits. TOPSIS is used to rank optimized solutions according to predefined objective weights. Farmers have been surveyed

to collect technical and economic data. Li et al., (2021), Yue and Guo, (2021), Yue et al., (2021) and Yue et al., (2022) combine MOO with AHP. Li et al., (2021) have combined MOO and AHP to find optimized strategic management solutions of agroforestry systems in Heilongjiang Province, China with a water-land-food-energy nexus multi-actor perspective. AHP has determined the objective weights of the three optimized dimensions: resource efficiency, the environmental dimension considering GHGs emissions and carbon sequestration and the economic dimension that accounts for the crop farming average benefits. A nonlinear multi-objective fractional program has been solved with compromise programming to derive strategic optimized resources management solutions. Yue and Guo, (2021), Yue et al., (2021) and Yue et al., (2022) combine MOO, AHP and stochastic programming to derive optimized multi-actor strategic management solutions of agricultural land in Zhanghe irrigation district, China under uncertainties. AHP is used to determine weights for economic, environmental and social objectives. Sun et al., (2022) combine game theory and TOPSIS based MCDM together with the coupling coordination model used by Cheng et al., (2023) and S. Wang et al., (2023) to develop an integrated evaluation index system of WEFN synergy. Game theory is used to optimize the combination of weights determined by three different weighting methods (order relation method, entropy weighting method, and variation coefficient method) and an enhanced TOPSIS model is used to compare the synergy level of nexus resources among thirty Chinese evaluated regions. Stakeholders intervene to assign weights to indicators for the order relation method. Each weights assignment method can be interpreted as different actors' preferences.

Table 14 gives key information on the three studies that combine mathematical modelling with participatory approaches.

Table 14: Studies that combine mathematical modelling and participatory approaches

Paper reference	Journal	Methods	Simulation resolution	Spatial scale	Temporal scale	Decision levels	SES modelling approach	Stakeholder involvement	Uncertainties and stochasticity
Wang et al., (2022)	Applied Soft Computing	Social analysis and mathematical models	Regional	Regional	Atemporal	Strategic	Policies are environment friendly	No	Incomplete fuzzy preference relations (IFPR)
Ghodsv ali et al., (2022)	Sustainable Cities and Society	Serious Game, MOO, Game Theory	Grid cells Year	District	30 years	Strategic	Environmental and social objectives	Yes	Not addressed
Ghodsv ali et al., (2023)	Computers, Environment and Urban Systems	Serious Game, MOO, Game Theory	Grid cells Year	District	30 years	Strategic	Environmental and social objectives	Yes	Not addressed

Wang et al., (2022) mix a social analysis graph model that integrates incomplete fuzzy preference relation (IPFR) with mathematical models to derive decision makers' preferences over a set of possible system states and to resolve conflict among stakeholders with different

preferences by achieving a stable state. Ghodsvali et al., (2022) have mixed multi-objective optimization, game theory and a serious game to obtain S.N.O.G (Spatial Nexus Optimization Game), an online serious game designed for stakeholders to develop sustainable strategic resource management scenarios of urban water-energy-food nexus systems. An enhanced Non-dominated Sorting Genetic Algorithm has been developed by Ghodsvali et al., (2023) to find optimized spatial land allocation policies. The game player allocates available policies to land pieces of the region under study at each simulation step to find scenarios that score better than the initial optimized scenario and that satisfy a coalition game between two optimization objectives: ecological stress minimization and social acceptance maximization. Suggested game policies have been designed with key stakeholders. To play the game in a multi-actor setting, stakeholders must meet in a room. The framework has been applied to a smart-eco district in the Netherlands for which simulations have run over a thirty-year period.

d. Discussion and recommendations

This section aims to answer the research questions introduced above and to emit recommendations. Figure 11 partly answers questions 1 and 2 by illustrating the modelling and simulation goals that can be attained by applying the distinct multi-actor approaches reviewed at different decision levels.

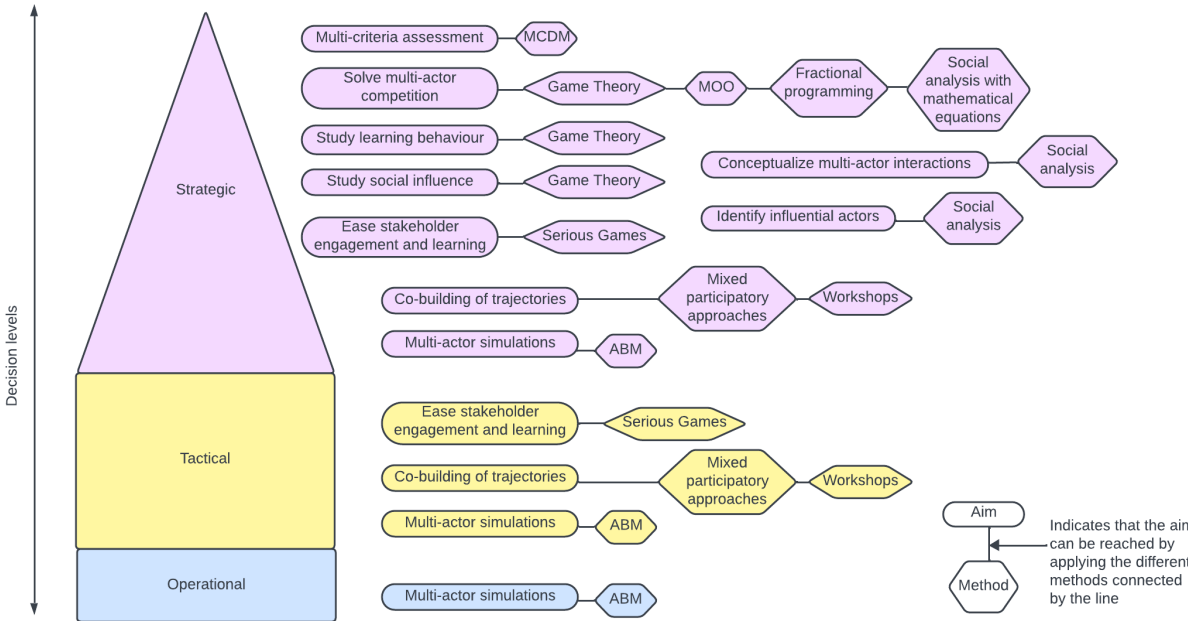


Figure 11: Goals that can be attained with multi-actor approaches at different decision levels

Operational multi-actor decision-making processes are only studied by agent-based models. Multi-agent based models simulate multi-actor interactions between different actors of the same socio-ecological WEFN system that make decisions at operational, tactical and strategic decision levels. To address multi-actor tactical decisions, multi-agent based models, workshops, mixed participatory approaches integrating workshops and serious games are used. Workshops and mixed participatory approaches integrating workshops enable multi-stakeholder building of trajectories by commonly identifying problems at hand, defining scenarios, selecting evaluation indicators and building conceptual models. Serious games

enable stakeholders to engage and learn about multi-actor decision-making processes and impacts. Strategic multi-actor decision-making processes are the most addressed. All methods applied to operational and tactical decision levels are also applied to study multi-actor strategic decisions. Additionally, all mathematical modelling approaches reviewed are applied to study multi-actor strategic decisions. Game theory enables the study of social influence and learning behaviors. Game theory can also find optimal resource management solutions to multi-actor competitive objectives. Optimal multi-actor strategic resource allocation schemes are also found by applying multi-objective optimization (MOO), fractional programming and social analysis techniques such as graph based techniques mixed with mathematical modelling. Social analysis techniques on their own enable the conceptualization of multi-actor strategic interactions. Multi-criteria decision-making (MCDM) techniques permit multi-actor multi-criteria integrated assessments of nexus systems. Regarding spatial scales, approaches address varied spatial scales, ranging from farm nexus systems to regional, national and transboundary systems. No link can be drawn between a particular approach and a particular spatial scale. Regarding temporal scales, social analysis studies are atemporal, and other approaches study systems for periods lasting an entire crop life cycle, to periods lasting a single year, to ten or twenty years. Table 15 summarizes how each multi-actor approach accounts for SES considerations, uncertainties and stakeholder engagement.

Table 15: SES considerations, uncertainties and stakeholder engagement in multi-actor approaches

	SES considerations	Uncertainties	Stakeholder engagement
ABM	<ul style="list-style-type: none"> - SES optimization objectives of optimization module within same framework - Include hydrological or biophysical models - Tracking of economic, environmental and social indicators - Analysis of socio-economic scenarios and impact assessments - Resources availabilities used as constraints 	<ul style="list-style-type: none"> - Monte Carlo simulations - Agents activities are randomized 	<ul style="list-style-type: none"> - ABM parametrized with stakeholder data
MOO	<ul style="list-style-type: none"> - SES optimization objectives - Implementation of social allocation schemes - Resources availabilities used as constraints 	<ul style="list-style-type: none"> - Surrogate models - Scenario analysis - Stochastic programming - Fuzzy logic theory 	<ul style="list-style-type: none"> - Co-design of optimization model and objectives
Game Theory	<ul style="list-style-type: none"> - SES optimization objectives - Include hydrological or biophysical models - Resources availabilities used as constraints 	<ul style="list-style-type: none"> - Ratings of ratings in trust framework - Chance constrained programming - Stochastic programming - Genetic algorithms 	<ul style="list-style-type: none"> - Get and validate input data
Fractional programming	<ul style="list-style-type: none"> - SES optimization objectives 	<ul style="list-style-type: none"> - Inexact fractional programming 	<ul style="list-style-type: none"> - Absent
Social analysis techniques	<ul style="list-style-type: none"> - Connections between actors and SES resources are modelled - Use of social interaction frameworks - Analysis of environmental friendly policies 	<ul style="list-style-type: none"> - Risk analysis - New links across sectors are built 	<ul style="list-style-type: none"> - Co-construction of social models
Workshops	<ul style="list-style-type: none"> - Include hydrological or biophysical models - Consideration of resources' states 	<ul style="list-style-type: none"> - Risk analysis - Scenario analysis 	<ul style="list-style-type: none"> - Workshops
Serious games	<ul style="list-style-type: none"> - Biophysical elements are considered 	<ul style="list-style-type: none"> - Not addressed 	<ul style="list-style-type: none"> - Game interface

Mixed participatory approaches	<ul style="list-style-type: none"> - Ecosystem services interpreted as system drivers - Tracking of economic, environmental and social indicators - Analysis of environmental friendly policies - Actors of SES system are connected between them 	- Not addressed	- Workshops
MCDM	<ul style="list-style-type: none"> - Economic, environmental and social indicators 	<ul style="list-style-type: none"> - Combination of subjective and objective weighting methods - Fuzzy logic theory - Entropy weighting 	- Subjective weights

Table 15 shows that SES considerations are included as optimization objectives of mathematical modelling approaches. Hydrological and biophysical models are included in the same frameworks as ABMs, game theory and workshops. Economic, environmental and social indicators are tracked by ABMs, mixed participatory approaches and they are evaluated by MCDM approaches. Socio-economic scenarios are simulated by ABMs and environmental friendly policies are analysed with participatory approaches (social analysis techniques and mixed participatory approaches). Resources availabilities are used as constraints for mathematical models (ABM, MOO and game theory). MOO are used together with social resource allocation schemes. Social analysis techniques conceptualize connections between system actors and SES resources and use social interaction frameworks. Workshops and serious games consider resources states' and biophysical elements and mixed participatory approaches consider ecosystem services as system drivers. ABM frameworks address uncertainties by running Monte Carlo simulations and randomizing agents' behaviours. Stakeholder data is used to parametrize ABMs. MOO frameworks address uncertainties through the use of surrogate models, scenario analysis, stochastic programming and fuzzy logic theory. MOO models can be co-designed with stakeholders. Game theory frameworks address uncertainties by introducing trust measures in social networks and by implementing stochastic and chance constrained programming as well as genetic algorithms. Stakeholders are sometimes consulted to give and validate input data. Fractional programming introduces SES objectives and uses inexact fractional programming to deal with uncertainties. Social analysis techniques and workshops analyse risks, build new links across sectors and analyse uncertain scenarios to deal with uncertainties. MCDM approaches combine subjective and weighting methods and use fuzzy logic to address uncertainties. Stakeholders intervene to define subjective weights.

Below are some recommendations according to the problem at hand:

- To study operational or multi-level decision-making processes: use ABMs.
- To ease stakeholder engagement at tactical and strategic decision levels: develop serious games.
- To co-build tactical or strategic trajectories, evaluation indicators or conceptualize multi-actor interactions: use participatory approaches.
- To identify strategic influential actors: use social analysis.

- To study strategic social influence and multi-actor learning behaviours: use game theory.
- To perform multi-criteria integrated assessment: use MCDM.
- To solve strategic multi-actor competitions and resource allocation conflicts: use game theory, MOO, fractional programming or mix social analysis with mathematical models.
- Mix approaches to benefit from functionalities from each approach.
- Refer to table 15 to know how to account for SES considerations, uncertainties and engage stakeholders for each multi-actor approach.

V. Conclusions and perspectives

Given the present state of water, energy and food resources and the general socio-economic and environmental contexts an energy transition cannot be overlooked and solutions are needed to better manage agricultural land and water use. The scientific community recommends the use of generic tools that simulate precise local conditions and local and regional actor's decision-making processes in a holistic integrated manner. It also advises the use of participatory approaches and tools that offer geospatial capabilities. The literature review of multi-actor integrated modelling approaches in the context of WEFN has examined sixty-two articles and classified them into mathematical modelling approaches, participatory approaches, multi-criteria decision making approaches and mixed approaches. The review has evidenced that studies from the socio-economic communities are still lacking. Multi-actor approaches have been linked to the decision levels at which they study multi-actor decision-making processes and solve multi-actor competitive conflicts. Emphasis has been drawn to the way they include socio-ecological considerations, account for uncertainties and engage stakeholders. Multi-agent based models are so far the only technique that enables operational simulations of multi-actor WEFN systems and multi-actor bottom-up approaches. They are consequently a promising tool that can be hybridized with other multi-actor accounting tools to derive multi-actor models that simulate multi-decision levels simultaneously and solve resource allocation conflicts between actors with confronting views.

We have therefore chosen to develop a multi-actor multi-level framework for water-energy-food systems that combines multi-agent based simulations with strategic multi-criteria decision-making methods or strategic multi-objective optimization. We have proved the framework's applicability by implementing it to design strategic scenarios of water-energy-food resource allocations in agricultural land. The implemented framework allocates best water-energy-food land-use alternatives at parcel level based on local or regional indicators. The methodology designed to implement the framework iterates between decision levels. Reference strategic scenarios are simulated at operational and tactical temporal and spatial scales with a multi-agent based platform. Outputs from these simulations are processed and used as inputs of multi-actor multi-criteria strategic decision-making methods or a multi-objective optimization problem. Chapter 2 presents generic tools and methodologies selected and developed to implement the framework for resource allocations in agricultural land.

VI. References

- Abdel-Aal, M., Haltas, I., Varga, L., 2020. Modelling the diffusion and operation of anaerobic digestions in Great Britain under future scenarios within the scope of water-energy-food nexus. *Journal of Cleaner Production* 253, 119897. <https://doi.org/10.1016/j.jclepro.2019.119897>
- Alasam Alzaabi, M.S.M., Mezher, T., 2021. Analyzing existing UAE national water, energy and food nexus related strategies. *Renewable and Sustainable Energy Reviews* 144, 111031. <https://doi.org/10.1016/j.rser.2021.111031>
- Albrecht, T.R., Crootof, A., Scott, C.A., 2018. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environ. Res. Lett.* 13, 043002. <https://doi.org/10.1088/1748-9326/aaa9c6>
- Alletto, L., Vandewalle, A., Debaeke, P., 2022. Crop diversification improves cropping system sustainability: An 8-year on-farm experiment in South-Western France. *Agricultural Systems* 200, 103433. <https://doi.org/10.1016/j.agsy.2022.103433>
- Almulla, Y., Ramirez, 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>
- Anejionu, O.C.D., Di Lucia, L., Woods, J., 2020. Geospatial modelling of environmental and socioeconomic impacts of large-scale production of advanced biofuel. *Biomass and Bioenergy* 142, 105789. <https://doi.org/10.1016/j.biombioe.2020.105789>
- Bahri, M., 2020. Analysis of the water, energy, food and land nexus using the system archetypes: A case study in the Jatiluhur reservoir, West Java, Indonesia. *Science of The Total Environment* 716, 137025. <https://doi.org/10.1016/j.scitotenv.2020.137025>
- Balaican, D., Nichersu, I., Nichersu, Iuliana.I., Pierce, A., Wilhelmi, O., Laborgne, P., Bratfanof, E., 2023. Creating knowledge about food-water-energy nexus at a local scale: A participatory approach in Tulcea, Romania. *Environmental Science & Policy* 141, 23–32. <https://doi.org/10.1016/j.envsci.2022.12.013>
- Bazzana, D., Gilioli, G., Simane, B., Zaitchik, B., 2021. Analyzing constraints in the water-energy-food nexus: The case of eucalyptus plantation in Ethiopia. *Ecological Economics* 180, 106875. <https://doi.org/10.1016/j.ecolecon.2020.106875>
- Bazzana, D., Gilioli, G., Zaitchik, B., 2020a. Impact of hydropower development on rural livelihood: An agent-based exploration. *Journal of Cleaner Production* 275, 122333. <https://doi.org/10.1016/j.jclepro.2020.122333>
- Bazzana, D., Zaitchik, B., Gilioli, G., 2020b. Impact of water and energy infrastructure on local well-being: an agent-based analysis of the water-energy-food nexus. *Structural Change and Economic Dynamics* 55, 165–176. <https://doi.org/10.1016/j.strueco.2020.08.003>
- Cansino-Loeza, B., Munguía-López, A. del C., Ponce-Ortega, J.M., 2022. A water-energy-food security nexus framework based on optimal resource allocation. *Environmental Science & Policy* 133, 1–16. <https://doi.org/10.1016/j.envsci.2022.03.006>
- Cansino-Loeza, B., Ponce-Ortega, J.M., 2021. Sustainable assessment of Water-Energy-Food Nexus at regional level through a multi-stakeholder optimization approach. *Journal of Cleaner Production* 290, 125194. <https://doi.org/10.1016/j.jclepro.2020.125194>

- Cheng, Y., Wang, J., Shu, K., 2023. The coupling and coordination assessment of food-water-energy systems in China based on sustainable development goals. *Sustainable Production and Consumption* 35, 338–348. <https://doi.org/10.1016/j.spc.2022.11.011>
- D'Amore, G., Di Vaio, A., Balsalobre-Lorente, D., Boccia, F., 2022. Artificial Intelligence in the Water–Energy–Food Model: A Holistic Approach towards Sustainable Development Goals. *Sustainability* 14, 867. <https://doi.org/10.3390/su14020867>
- Dehghan, H., Nahavandi, N., Chaharsooghi, S.K., Zarei, J., Amin-Naseri, M.R., 2022. A hybrid game theory and system dynamics model to determine optimal electricity generation mix. *Computers & Chemical Engineering* 166, 107990. <https://doi.org/10.1016/j.compchemeng.2022.107990>
- Di Martino, M., Linke, P., Pistikopoulos, E.N., 2023. A comprehensive classification of food–energy–water nexus optimization studies: State of the art. *Journal of Cleaner Production* 420, 138293. <https://doi.org/10.1016/j.jclepro.2023.138293>
- Elkamel, M., Valencia, A., Zhang, W., Zheng, Q.P., Chang, N.-B., 2023. Multi-agent modelling for linking a green transportation system with an urban agriculture network in a food-energy-water nexus. *Sustainable Cities and Society* 89, 104354. <https://doi.org/10.1016/j.scs.2022.104354>
- Emamjomehzadeh, O., Kerachian, R., Emami-Skardi, M.J., Momeni, M., 2023. Combining urban metabolism and reinforcement learning concepts for sustainable water resources management: A nexus approach. *Journal of Environmental Management* 329, 117046. <https://doi.org/10.1016/j.jenvman.2022.117046>
- Falconer, R.E., Haltas, I., Varga, L., Forbes, P.J., Abdel-Aal, M., Panayotov, N., 2020. Anaerobic Digestion of food waste: Eliciting sustainable water-energy-food nexus practices with Agent Based Modelling and visual analytics. *Journal of Cleaner Production* 255, 120060. <https://doi.org/10.1016/j.jclepro.2020.120060>
- Franz, M., Schlitz, N., Schumacher, K.P., 2018. Globalization and the water-energy-food nexus – Using the global production networks approach to analyze society-environment relations. *Environmental Science & Policy* 90, 201–212. <https://doi.org/10.1016/j.envsci.2017.12.004>
- Gerbaud, V., 2023. PSE prospective: Paradigm transition towards Complex Thought in a global world under pressure. *Computers & Chemical Engineering* 175, 108274. <https://doi.org/10.1016/j.compchemeng.2023.108274>
- Ghodsvali, M., Dane, G., de Vries, B., 2022. An online serious game for decision-making on food-water-energy nexus policy. *Sustainable Cities and Society* 87, 104220. <https://doi.org/10.1016/j.scs.2022.104220>
- Ghodsvali, M., Krishnamurthy, S., De Vries, B., 2019. Review of transdisciplinary approaches to food-water-energy nexus: A guide towards sustainable development. *Environmental Science & Policy* 101, 266–278. <https://doi.org/10.1016/j.envsci.2019.09.003>
- Ghozatfar, A., Yaghoubi, S., 2023. A cooperation approach for nexus among biofuel, compost, and water in waste supply chain under risk aversion: A case study. *Computers & Chemical Engineering* 108334. <https://doi.org/10.1016/j.compchemeng.2023.108334>
- González-Bravo, R., Mahlkecht, J., Ponce-Ortega, J.M., 2018. Water, food and power grid optimization at macroscopic level involving multi-stakeholder approach. *Energy Procedia*, 5th International Conference on Energy and Environment Research, ICEER

- 2018, 23-27 July 2018, Prague, Czech Republic 153, 347–352.
<https://doi.org/10.1016/j.egypro.2018.10.013>
- Gu, D., Guo, J., Fan, Y., Zuo, Q., Yu, L., 2022. Evaluating water-energy-food system of Yellow River basin based on type-2 fuzzy sets and Pressure-State-Response model. *Agricultural Water Management* 267, 107607.
<https://doi.org/10.1016/j.agwat.2022.107607>
- Guo, M., van Dam, K.H., Touhami, N.O., Nguyen, R., Delval, F., Jamieson, C., Shah, N., 2020. Multi-level system modelling of the resource-food-bioenergy nexus in the global south. *Energy* 197, 117196. <https://doi.org/10.1016/j.energy.2020.117196>
- Guo, S., Zhang, F., Engel, B.A., Wang, Y., Guo, P., Li, Y., 2022. A distributed robust optimization model based on water-food-energy nexus for irrigated agricultural sustainable development. *Journal of Hydrology* 606, 127394.
<https://doi.org/10.1016/j.jhydrol.2021.127394>
- Hachaichi, M., Egieya, J., 2023. Water-Food-Energy Nexus in Global Cities: Addressing Complex Urban Interdependencies. *Water Resour Manage* 37, 1811–1825.
<https://doi.org/10.1007/s11269-023-03455-7>
- Haltas, I., Suckling, J., Soutar, I., Druckman, A., Varga, L., 2017. Anaerobic digestion: a prime solution for water, energy and food nexus challenges. *Energy Procedia, Proceedings of 1st International Conference on Sustainable Energy and Resource Use in Food Chains including Symposium on Heat Recovery and Efficient Conversion and Utilisation of Waste Heat ICSEF 2017, 19-20 April 2017, Windsor UK* 123, 22–29.
<https://doi.org/10.1016/j.egypro.2017.07.280>
- Hoff, H., 2011. Understanding the Nexus.
- Huang, K., Dai, L., Yu, L., Fan, Y., Huang, G., Xiao, Y., Wu, Q., 2022. Planning regional-scale water-energy-food nexus system management under uncertainty: An inexact fractional programming method. *Journal of Contaminant Hydrology* 247, 103985.
<https://doi.org/10.1016/j.jconhyd.2022.103985>
- International Energy Agency, 2020. Electricity Market Report. OECD.
<https://doi.org/10.1787/f0aed4e6-en>
- Irabien, A., Darton, R.C., 2016. Energy–water–food nexus in the Spanish greenhouse tomato production. *Clean Techn Environ Policy* 18, 1307–1316.
<https://doi.org/10.1007/s10098-015-1076-9>
- Kalvani, S.R., Celico, F., 2023. The Water-Energy-Food Nexus in European Countries: A Review and Future Perspectives. *Sustainability* 15, 4960.
<https://doi.org/10.3390/su15064960>
- Karamian, F., Mirakzadeh, A.A., Azari, A., 2023. Application of multi-objective genetic algorithm for optimal combination of resources to achieve sustainable agriculture based on the water-energy-food nexus framework. *Science of The Total Environment* 860, 160419. <https://doi.org/10.1016/j.scitotenv.2022.160419>
- Kaufmann, P., Stagl, S., Franks, D.W., 2009. Simulating the diffusion of organic farming practices in two New EU Member States. *Ecological Economics* 68, 2580–2593.
<https://doi.org/10.1016/j.ecolecon.2009.04.001>
- Kramer, A., Blumstein, D.S., 2021. Understanding the opportunities and challenges of the WEFN Nexus.
- Li, M., Li, H., Fu, Q., Liu, D., Yu, L., Li, T., 2021. Approach for optimizing the water-land-food-energy nexus in agroforestry systems under climate change. *Agricultural Systems* 192, 103201. <https://doi.org/10.1016/j.agsy.2021.103201>

- Ma, Y., Li, Y.P., Zhang, Y.F., Huang, G.H., 2021. Mathematical modelling for planning water-food-ecology-energy nexus system under uncertainty: A case study of the Aral Sea Basin. *Journal of Cleaner Production* 308, 127368. <https://doi.org/10.1016/j.jclepro.2021.127368>
- Maali, Y., 2009. A multiobjective approach for solving cooperative n-person games. *International Journal of Electrical Power & Energy Systems* 31, 608–610. <https://doi.org/10.1016/j.ijepes.2009.06.021>
- Magliocca, N.R., 2020. Agent-Based Modelling for Integrating Human Behavior into the Food–Energy–Water Nexus. *Land* 9, 519. <https://doi.org/10.3390/land9120519>
- Märker, C., Venghaus, S., Hake, J.-F., 2018. Integrated governance for the food–energy–water nexus – The scope of action for institutional change. *Renewable and Sustainable Energy Reviews* 97, 290–300. <https://doi.org/10.1016/j.rser.2018.08.020>
- Medina-Santana, A.A., Flores-Tlacuahuac, A., Cárdenas-Barrón, L.E., Fuentes-Cortés, L.F., 2020. Optimal design of the water-energy-food nexus for rural communities. *Computers & Chemical Engineering* 143, 107120. <https://doi.org/10.1016/j.compchemeng.2020.107120>
- Mochizuki, J., Magnuszewski, P., Pajak, M., Krolikowska, K., Jarzabek, L., Kulakowska, M., 2021. Simulation games as a catalyst for social learning: The case of the water-food-energy nexus game. *Global Environmental Change* 66, 102204. <https://doi.org/10.1016/j.gloenvcha.2020.102204>
- Mosalam, H.A., El-Barad, M., 2020. Design of an integration platform between the water-energy nexus and a business model applied for sustainable development. *Water Science and Technology* 81, 1398–1405. <https://doi.org/10.2166/wst.2020.212>
- Namany, S., Al-Ansari, T., Govindan, R., 2019. Sustainable energy, water and food nexus systems: A focused review of decision-making tools for efficient resource management and governance. *Journal of Cleaner Production* 225, 610–626. <https://doi.org/10.1016/j.jclepro.2019.03.304>
- Namany, S., Govindan, R., Al-Ansari, T., 2023. Operationalising transboundary cooperation through game theory: An energy water food nexus approach for the Middle East and North Africa. *Futures* 152, 103198. <https://doi.org/10.1016/j.futures.2023.103198>
- Namany, S., Govindan, R., Di Martino, M., Pistikopoulos, E.N., Linke, P., Avraamidou, S., Al-Ansari, T., 2022. Developing intelligence in food security: An agent-based modelling approach of Qatar’s food system interactions under socio-economic and environmental considerations. *Sustainable Production and Consumption* 32, 669–689. <https://doi.org/10.1016/j.spc.2022.05.017>
- Namany, S., Govindan, R., Martino, M.D., Pistikopoulos, E.N., Linke, P., Avraamidou, S., Al-Ansari, T., 2021. An Energy-Water-Food Nexus-based Decision-making Framework to Guide National Priorities in Qatar. *Sustainable Cities and Society* 75, 103342. <https://doi.org/10.1016/j.scs.2021.103342>
- Naranjo, L., Correa-Cano, M.E., Rey, D., Chengot, R., España, F., Sactic, M., Knox, J.W., Yan, X., Viteri-Salazar, O., Foster, W., Melo, O., 2023. A scenario-specific nexus modelling toolkit to identify trade-offs in the promotion of sustainable irrigated agriculture in Ecuador, a Belt and Road country. *Journal of Cleaner Production* 413, 137350. <https://doi.org/10.1016/j.jclepro.2023.137350>
- Nhamo, L., Mabhaudhi, T., Mpandeli, S., Dickens, C., Nhemachena, C., Senzanje, A., Naidoo, D., Liphadzi, S., Modi, A.T., 2020. An integrative analytical model for the water-

- energy-food nexus: South Africa case study. *Environmental Science & Policy* 109, 15–24. <https://doi.org/10.1016/j.envsci.2020.04.010>
- Nie, Y., Avraamidou, S., Xiao, X., Pistikopoulos, E.N., Li, J., Zeng, Y., Song, F., Yu, J., Zhu, M., 2019. A Food-Energy-Water Nexus approach for land use optimization. *Science of The Total Environment* 659, 7–19. <https://doi.org/10.1016/j.scitotenv.2018.12.242>
- Opejin, A.K., Aggarwal, R.M., White, D.D., Jones, J.L., Maciejewski, R., Mascaro, G., Sarjoughian, H.S., 2020. A Bibliometric Analysis of Food-Energy-Water Nexus Literature. *Sustainability* 12, 1112. <https://doi.org/10.3390/su12031112>
- Pahl-Wostl, C., 2019. Governance of the water-energy-food security nexus: A multi-level coordination challenge. *Environmental Science & Policy* 92, 356–367. <https://doi.org/10.1016/j.envsci.2017.07.017>
- Peña-Torres, D., Boix, M., Montastruc, L., 2022. Optimization approaches to design water-energy-food nexus: A literature review. *Computers & Chemical Engineering* 167, 108025. <https://doi.org/10.1016/j.compchemeng.2022.108025>
- Phetheet, J., Hill, M.C., Barron, R.W., Gray, B.J., Wu, H., Amanor-Boadu, V., Heger, W., Kisekka, I., Golden, B., Rossi, M.W., 2021. Relating agriculture, energy, and water decisions to farm incomes and climate projections using two freeware programs, FEWCalc and DSSAT. *Agricultural Systems* 193, 103222. <https://doi.org/10.1016/j.agsy.2021.103222>
- Purwanto, A., Sušnik, J., Suryadi, F.X., de Fraiture, C., 2021. Water-Energy-Food Nexus: Critical Review, Practical Applications, and Prospects for Future Research. *Sustainability* 13, 1919. <https://doi.org/10.3390/su13041919>
- Purwanto, A., Sušnik, J., Suryadi, F.X., de Fraiture, C., 2019. Using group model building to develop a causal loop mapping of the water-energy-food security nexus in Karawang Regency, Indonesia. *Journal of Cleaner Production* 240, 118170. <https://doi.org/10.1016/j.jclepro.2019.118170>
- Radmehr, R., Ghorbani, M., Ziaei, A.N., 2021. Quantifying and managing the water-energy-food nexus in dry regions food insecurity: New methods and evidence. *Agricultural Water Management* 245, 106588. <https://doi.org/10.1016/j.agwat.2020.106588>
- Ramos, M.A., Boix, M., Aussel, D., Montastruc, L., Domenech, S., 2016. Water integration in eco-industrial parks using a multi-leader-follower approach. *Computers & Chemical Engineering* 87, 190–207. <https://doi.org/10.1016/j.compchemeng.2016.01.005>
- Rasmusen, E., 2006. *Games and Information: An Introduction to Game Theory*. Wiley.
- Rotmans, J., Van Asselt, M., 1996. Integrated assessment: A growing child on its way to maturity. *Climatic Change* 34, 327–336. <https://doi.org/10.1007/BF00139296>
- Segovia-Hernández, J.G., Contreras-Zarazúa, G., Ramírez-Márquez, C., 2023. Sustainable design of water–energy–food nexus: a literature review. *RSC Sustain.* <https://doi.org/10.1039/D3SU00110E>
- Shu, Q., Scott, M., Todman, L., McGrane, S.J., 2021. Development of a prototype composite index for resilience and security of water-energy-food (WEF) systems in industrialised nations. *Environmental and Sustainability Indicators* 11, 100124. <https://doi.org/10.1016/j.indic.2021.100124>
- Stein, C., Pahl-Wostl, C., Barron, J., 2018. Towards a relational understanding of the water-energy-food nexus: an analysis of embeddedness and governance in the Upper Blue Nile region of Ethiopia. *Environmental Science & Policy* 90, 173–182. <https://doi.org/10.1016/j.envsci.2018.01.018>

- Stylianopoulou, K., Papapostolou, C., Kondili, E., 2020. Water–Energy–Food Nexus: A Focused Review on Integrated Methods. *Environmental Sciences Proceedings* 2, 46. <https://doi.org/10.3390/environsciproc2020002046>
- Sun, L., Niu, D., Yu, M., Li, M., Yang, X., Ji, Z., 2022. Integrated assessment of the sustainable water-energy-food nexus in China: Case studies on multi-regional sustainability and multi-sectoral synergy. *Journal of Cleaner Production* 334, 130235. <https://doi.org/10.1016/j.jclepro.2021.130235>
- Sušnik, J., Masia, S., Indriksone, D., Brēmere, I., Vamvakeridou-Lydroudia, L., 2021. System dynamics modelling to explore the impacts of policies on the water-energy-food-land-climate nexus in Latvia. *Science of The Total Environment* 775, 145827. <https://doi.org/10.1016/j.scitotenv.2021.145827>
- Sušnik, J., Staddon, C., 2022. Evaluation of Water-Energy-Food (WEF) Nexus Research: Perspectives, Challenges, and Directions for Future Research. *J American Water Resour Assoc* 58, 1189–1198. <https://doi.org/10.1111/1752-1688.12977>
- Taguta, C., Senzanje, A., Kiala, Z., Malota, M., Mabhaudhi, T., 2022. Water-Energy-Food Nexus Tools in Theory and Practice: A Systematic Review. *Frontiers in Water* 4.
- Tan, Y.D., Lim, J.S., Andiappan, V., Wan Alwi, S.R., 2021. Cooperative game-based anchor process allocation within sustainable palm oil based complex for environment-food-energy-water nexus evaluation. *Journal of Cleaner Production* 314, 127927. <https://doi.org/10.1016/j.jclepro.2021.127927>
- Tilt, J.H., Mondo, H.A., Giles, N.A., Rivera, S., Babbar-Sebens, M., 2022. Demystifying the fears and myths: The co-production of a regional food, energy, water (FEW) nexus conceptual model. *Environmental Science & Policy* 132, 69–82. <https://doi.org/10.1016/j.envsci.2022.02.011>
- Tye, M.R., Wilhelmi, O.V., Pierce, A.L., Sharma, S., Nichersu, Iuliana, Wróblewski, M., Goszczyński, W., Wendel, J., Laborgne, P., Heyder, M., Nichersu, Iulian, 2022. The food water energy nexus in an urban context: Connecting theory and practice for nexus governance. *Earth System Governance* 12, 100143. <https://doi.org/10.1016/j.esg.2022.100143>
- United Nations Department of Economic and Social Affairs, 2022. *A World of 8 Billion*.
- Uslu, S., Kaur, D., Rivera, S.J., Duresi, A., Babbar-Sebens, M., Tilt, J.H., 2021. A Trustworthy Human–Machine framework for collective decision making in Food–Energy–Water management: The role of trust sensitivity. *Knowledge-Based Systems* 213, 106683. <https://doi.org/10.1016/j.knosys.2020.106683>
- Valencia, A., Zhang, W., Chang, N.-B., 2022. Sustainability transitions of urban food-energy-water-waste infrastructure: A living laboratory approach for circular economy. *Resources, Conservation and Recycling* 177, 105991. <https://doi.org/10.1016/j.resconrec.2021.105991>
- Viccaro, M., Caniani, D., Masi, S., Romano, S., Cozzi, M., 2022. Biofuels or not biofuels? The “Nexus Thinking” in land suitability analysis for energy crops. *Renewable Energy* 187, 1050–1064. <https://doi.org/10.1016/j.renene.2022.02.008>
- Wang, D., Huang, J., Xu, Y., Wu, N., 2022. Water–Energy–Food nexus evaluation using an inverse approach of the graph model for conflict resolution based on incomplete fuzzy preferences. *Applied Soft Computing* 120, 108703. <https://doi.org/10.1016/j.asoc.2022.108703>
- Wang, J., Wei, J., Shan, W., Zhao, J., 2023. Modelling the water-energy-food-environment nexus and transboundary cooperation opportunity in the Brahmaputra River Basin.

- Journal of Hydrology: Regional Studies 49, 101497.
<https://doi.org/10.1016/j.ejrh.2023.101497>
- Wang, S., Yang, J., Wang, A., Liu, T., Du, S., Liang, S., 2023. Coordinated analysis and evaluation of water–energy–food coupling: A case study of the Yellow River basin in Shandong Province, China. *Ecological Indicators* 148, 110138.
<https://doi.org/10.1016/j.ecolind.2023.110138>
- Wang, X., van Dam, K.H., Triantafyllidis, C., Koppelaar, R.H.E.M., Shah, N., 2019. Energy-water nexus design and operation towards the sustainable development goals. *Computers & Chemical Engineering* 124, 162–171.
<https://doi.org/10.1016/j.compchemeng.2019.02.007>
- Yang, J., Yang, Y.C.E., Chang, J., Zhang, J., Yao, J., 2019. Impact of dam development and climate change on hydroecological conditions and natural hazard risk in the Mekong River Basin. *Journal of Hydrology* 579, 124177.
<https://doi.org/10.1016/j.jhydrol.2019.124177>
- Yuan, M.-H., Chiueh, P.-T., Lo, S.-L., 2021. Measuring urban food-energy-water nexus sustainability: Finding solutions for cities. *Science of The Total Environment* 752, 141954. <https://doi.org/10.1016/j.scitotenv.2020.141954>
- Yue, Q., Guo, P., 2021. Managing agricultural water-energy-food-environment nexus considering water footprint and carbon footprint under uncertainty. *Agricultural Water Management* 252, 106899. <https://doi.org/10.1016/j.agwat.2021.106899>
- Yue, Q., Guo, P., Wu, H., Wang, Y., Zhang, C., 2022. Towards sustainable circular agriculture: An integrated optimization framework for crop-livestock-biogas-crop recycling system management under uncertainty. *Agricultural Systems* 196, 103347.
<https://doi.org/10.1016/j.agsy.2021.103347>
- Yue, Q., Wu, H., Wang, Y., Guo, P., 2021. Achieving sustainable development goals in agricultural energy-water-food nexus system: An integrated inexact multi-objective optimization approach. *Resources, Conservation and Recycling* 174, 105833.
<https://doi.org/10.1016/j.resconrec.2021.105833>
- Zhang, F., Cai, Y., Tan, Q., Engel, B.A., Wang, X., 2021. An optimal modelling approach for reducing carbon footprint in agricultural water-energy-food nexus system. *Journal of Cleaner Production* 316, 128325. <https://doi.org/10.1016/j.jclepro.2021.128325>
- Zhang, T., Tan, Q., Zhang, S., Zhang, Tianyuan, Zhang, W., 2021. A participatory methodology for characterizing and prescribing water-energy-food nexus based on improved casual loop diagrams. *Resources, Conservation and Recycling* 164, 105124.
<https://doi.org/10.1016/j.resconrec.2020.105124>
- Zhou, Y., Chang, F.-J., Chang, L.-C., Lee, W.-D., Huang, A., Xu, C.-Y., Guo, S., 2020. An advanced complementary scheme of floating photovoltaic and hydropower generation flourishing water-food-energy nexus synergies. *Applied Energy* 275, 115389. <https://doi.org/10.1016/j.apenergy.2020.115389>
- Zuo, Q., Li, Q., Yang, L., Jing, R., Ma, J., Yu, L., 2023. Incorporating carbon sequestration toward a water-energy-food-carbon planning with uncertainties. *iScience* 26, 107669.
<https://doi.org/10.1016/j.isci.2023.107669>

VII. Appendices

Appendix A. All papers reviewed per multi-actor approach

Paper reference	Journal	Research Area	Multi-actor approach	Sub category	Multi-actor approach goal
Bieber et al., (2018)	Energy Policy	Energy	Mathematical modelling	ABM	Produce demand data
Abdel-Aal et al., (2020)	Journal of Cleaner Production	Environmental Studies	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Bazzana et al., (2020)	Journal of Cleaner Production	Environmental Studies	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Elkamel et al., (2023)	Sustainable Cities and Society	Environmental Studies	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Uslu et al., (2021)	Knowledge-Based Systems	Computer Science	Mathematical modelling	Game Theory	Study social influence
Haltas et al., (2017)	Energy Procedia	Energy	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Emamjomehzadeh et al., (2023)	Journal of Environmental Management	Environmental Studies	Mathematical modelling	Game Theory	Simulate agent's decision making processes
Cansino-Loeza and Ponce-Ortega, (2021)	Journal of Cleaner Production	Environmental Studies	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
Zuo et al., (2023)	iScience	Environmental Studies	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
Karamian et al., (2023)	Science of The Total Environment	Environmental Studies	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
Zhou et al., (2020)	Applied Energy	Energy	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
González-Bravo et al., (2018)	Energy Procedia	Energy	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
Avraamidou et al., (2018)	Science of The Total Environment	Environmental Studies	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
Cansino-Loeza et al., (2022)	Environmental Science & Policy	Environmental Studies	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
Ma et al., (2021)	Journal of Cleaner Production	Environmental Studies	Mathematical modelling	Game Theory	Strategic resource use optimization
Zhang et al., (2021)	Journal of Cleaner Production	Environmental Studies	Mathematical modelling	Game Theory	Strategic resource use optimization
J. Wang et al., (2023)	Journal of Hydrology: Regional Studies	Water	Mathematical modelling	Game Theory	Strategic resource use optimization
Phetheet et al., (2021)	Agricultural Systems	Food	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Kaufmann et al., (2009)	Ecological Economics	Socioeconomic	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Bazzana et al., (2020b)	Structural Change and Economic Dynamics	Socioeconomic	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Ding et al., (2021)	Resources, Conservation and Recycling	Environmental Studies	Mathematical modelling	ABM	Produce demand data and explore multi-actor interaction scenarios
Bazzana et al., (2021)	Ecological Economics	Socioeconomic	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Yang et al., (2019)	Journal of Hydrology	Water	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Namany et al., (2022)	Sustainable Production and Consumption	Environmental Studies	Mathematical modelling	ABM	Explore multi-actor interaction scenarios
Guo et al., (2022)	Journal of Hydrology	Water	Mathematical modelling	Multi-objective optimization (MOO)	Strategic resource use optimization
Huang et al., (2022)	Journal of Contaminant Hydrology	Water	Mathematical modelling	Fractional programming	Strategic resource use optimization
Tan et al., (2021)	Journal of Cleaner Production	Food	Mathematical modelling	Game Theory	Strategic resource use optimization
Mochizuki et al., (2021)	Global Environmental Change	Environmental Studies	Participatory approach	Serious Game	Ease stakeholder engagement
Naranjo et al., (2023)	Journal of Cleaner Production	Environmental Studies	Participatory approach	Workshops	Scenarios definition
Almulla et al., (2022)	Energy for Sustainable Development	Energy	Participatory approach	Workshops	Problem, scenarios and evaluation metrics definition
Alletto et al., (2022)	Agricultural Systems	Food	Participatory approach	Workshops and serious game	System design and ease stakeholder engagement
Bahri, (2020)	Science of The Total Environment	Environmental Studies	Participatory approach	Social analysis	Conceptualize multi-actor connections
Pahl-Wostl, (2019)	Environmental Science & Policy	Environmental Studies	Participatory approach	Social analysis	Conceptualize multi-actor connections
Stein et al., (2018)	Environmental Science & Policy	Environmental Studies	Participatory approach	Social analysis	Identify influential actors
Franz et al., (2018)	Environmental Science & Policy	Environmental Studies	Participatory approach	Social analysis	Conceptualize multi-actor connections
Märker et al., (2018)	Renewable and Sustainable Energy Reviews	Energy	Participatory approach	Social analysis	Conceptualize multi-actor connections
Balaican et al., (2023)	Environmental Science & Policy	Environmental Studies	Participatory approach	Digital tool and workshops	Problem definition and stakeholder engagement
Tilt et al., (2022)	Environmental Science & Policy	Environmental Studies	Participatory approach	Workshops	Scenarios and conceptual model definition
T. Zhang et al., (2021)	Resources, Conservation and Recycling	Environmental Studies	Participatory approach	Social analysis	Conceptualize multi-actor connections
Sušnik et al., (2021)	Science of The Total Environment	Environmental Studies	Participatory approach	Workshops, social analysis and serious game	Scenarios and conceptual model definition, conceptualize multi-actor connections and ease stakeholder engagement
Purwanto et al., (2019)	Journal of Cleaner Production	Environmental Studies	Participatory approach	Social analysis and workshops	Conceptualize multi-actor connections, conceptual model definition
Alasam Alzaabi and Mezher, (2021)	Renewable and Sustainable Energy Reviews	Energy	Participatory approach	Social analysis	Identify influential actors
Anejionu et al., (2020)	Biomass and Bioenergy	Energy	Participatory approach	Digital tool and workshops	Problem, scenarios and evaluation metrics definition, stakeholder engagement
Namany et al., (2021)	Sustainable Cities and Society	Environmental Studies	Multi Criteria Decision Making (MCDM)	AHP based MCDM	Integrated multi-actor assessment
Nhamo et al., (2020)	Environmental Science & Policy	Environmental Studies	Multi Criteria Decision Making (MCDM)	AHP based MCDM	Integrated multi-actor assessment
Yuan et al., (2021)	Science of The Total Environment	Environmental Studies	Multi Criteria Decision Making (MCDM)	AHP based MCDM	Integrated multi-actor assessment
Shu et al., (2021)	Environmental and Sustainability Indicators	Environmental Studies	Multi Criteria Decision Making (MCDM)	AHP based MCDM	Integrated multi-actor assessment
Wang et al., (2023)	Ecological Indicators	Environmental Studies	Multi Criteria Decision Making (MCDM)	AHP based MCDM	Integrated multi-actor assessment
Cheng et al., (2023)	Sustainable Production and Consumption	Environmental Studies	Multi Criteria Decision Making (MCDM)	AHP based MCDM	Integrated multi-actor assessment
Gu et al., (2022)	Agricultural Water Management	Water	Multi Criteria Decision Making (MCDM)	AHP and TOPSIS based MCDM	Integrated multi-actor assessment
Viccaro et al., (2022)	Renewable Energy	Energy	Multi Criteria Decision Making (MCDM)	AHP based MCDM	Integrated multi-actor assessment
Valencia et al., (2022)	Resources, Conservation and Recycling	Environmental Studies	Multi Criteria Decision Making (MCDM)	TOPSIS based MCDM	Integrated multi-actor assessment
Sun et al., (2022)	Journal of Cleaner Production	Environmental Studies	Mathematical modeling and Multi Criteria Decision Making (MCDM)	Game Theory and TOPSIS based MCDM	Integrated multi-actor assessment
Radmehr et al., (2021)	Agricultural Water Management	Water	Mathematical modeling and Multi Criteria Decision Making (MCDM)	MOO and TOPSIS based MCDM	Strategic resource use optimization and integrated multi-actor assessment
Yue and Guo, (2021)	Agricultural Water Management	Water	Mathematical modeling and Multi Criteria Decision Making (MCDM)	MOO and AHP based MCDM	Strategic resource use optimization and integrated multi-actor assessment
Yue et al., (2021)	Resources, Conservation and Recycling	Environmental Studies	Mathematical modeling and Multi Criteria Decision Making (MCDM)	MOO and AHP based MCDM	Strategic resource use optimization and integrated multi-actor assessment
Li et al., (2021)	Agricultural Systems	Food	Mathematical modeling and Multi Criteria Decision Making (MCDM)	MOO and AHP based MCDM	Strategic resource use optimization and integrated multi-actor assessment
Yue et al., (2022)	Agricultural Systems	Food	Mathematical modeling and Multi Criteria Decision Making (MCDM)	MOO and AHP based MCDM	Strategic resource use optimization and integrated multi-actor assessment
Falconer et al., (2020)	Journal of Cleaner Production	Environmental Studies	Mathematical modeling and Multi Criteria Decision Making (MCDM)	ABM and TOPSIS based MCDM	Explore multi-actor interaction scenarios, strategic resource use optimization and integrated multi-actor assessment
Ghodvali et al., (2022)	Sustainable Cities and Society	Environmental Studies	Participatory approach and mathematical modelling	Serious Game, MOO, Game Theory	Ease stakeholder engagement, strategic resource use optimization and integrated multi-actor assessment
Ghodvali et al., (2023)	Computers, Environment and Urban Systems	Computer Science	Participatory approach and mathematical modelling	Serious Game, MOO, Game Theory	Ease stakeholder engagement, strategic resource use optimization and integrated multi-actor assessment
Wang et al., (2022)	Applied Soft Computing	Computer Science	Participatory approach and mathematical modelling	Social analysis and mathematical models	Conceptualize multi-actor connections

Chapter 2: Operational simulation tools and multi-criteria strategic indicators for WEFN systems

I. Introduction

Chapter 1 has depicted the socio-economic, environmental and scientific contexts around water-energy-food systems. Chapter 2 presents the operational tools and multi-criteria strategic indicators selected and developed to implement the generic multi-level multi-actor framework for water-energy-food nexus systems designed throughout this Phd work and illustrated in Figure 1. The framework combines operational and tactical multi-agent based simulations with strategic decision-making methods. The framework iterates between decision-levels because strategic data is used to parametrize operational and tactical multi-agent based simulations and outputs from these simulations become inputs of strategic decision-making methods. The framework's novelty lies in accounting for geographical dependencies and simulating nexus actors that act under operational, tactical and strategic constraints. For this manuscript, the framework has been applied to determine land-use allocations towards the energy and food supply sectors by finding best ways to allocate renewable energy production units in agricultural land. For our case study, the agricultural parcel and a daily time step characterize the operational scale, the tactical scale addresses farm level and cropping season issues and the strategic scale considers whole territory and yearly dynamics and objectives.

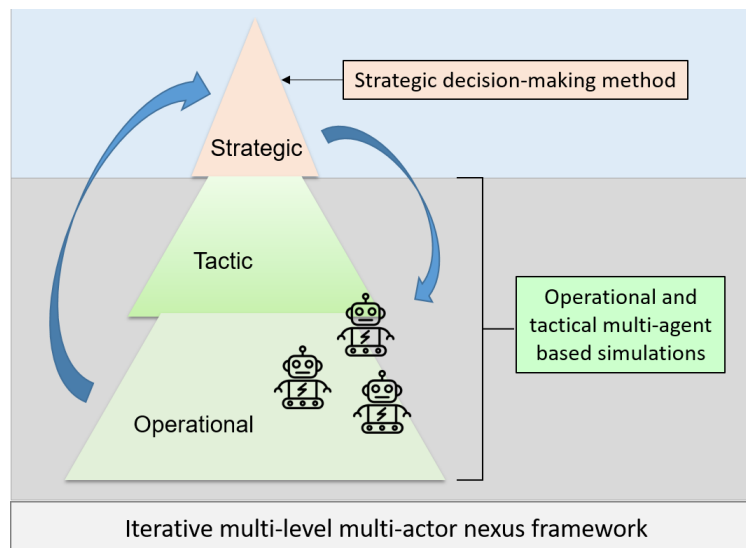


Figure 1: Generic multi-level multi-actor framework for WEFN systems

Figure 2 depicts the methodological workflow sketched to implement our multi-actor multi-level WEFN framework. The first step of the workflow identifies a case study territory where better management of water, energy and food resources is needed. The second step collects data and

identifies possible resource management configurations. For land-use allocation problems in agricultural territories, the second step undertakes an agricultural land suitability study for solar panels and wind turbines. Territorial resource management scenarios are defined in step 3. Step 4 simulates scenarios defined in step 3 at operational and tactical scales with a multi-agent based platform. MAELIA (Therond et al., 2014), a French multi-agent based platform, is used to simulate operational scenarios of the French case study territory used to illustrate our framework and presented in the next chapter. Step 5 computes multi-criteria performance indicators and step 6 implements strategic decision-making methods. This chapter depicts the elements that appear in orange font in Figure 2.

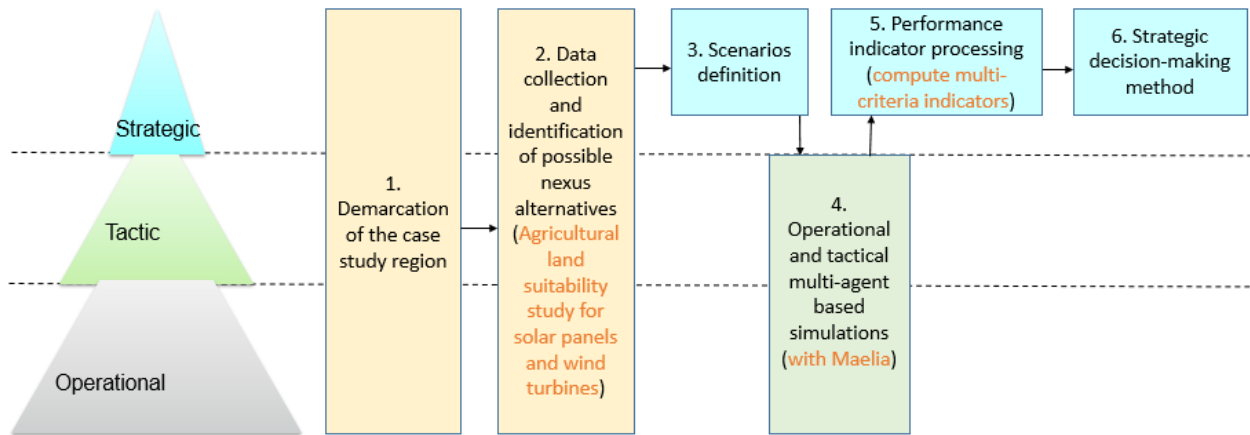


Figure 2: Methodological workflow for our multi-level multi-actor WEFN framework

Chapter 2 starts describing the multi-agent based platform selected to simulate nexus systems of our case study territory at operational scales. It pursues explaining the methodology developed to evaluate the suitability of agricultural land for solar panels and wind turbines. It ends by displaying the multi-sector indicators selected and developed to characterize and evaluate WEFN systems and scenarios. These are used to implement strategic multi-criteria decision-making and multi-objective optimization methods in step 6 of the methodology shown in Figure 1. Chapter 3 and 4 present the strategic decision-making methods developed for our framework.

II. MAELIA to model multi-agent operational nexus systems

a. Overview

MAELIA is a spatialized multi-agent based platform developed to model and simulate agricultural dynamic systems. The acronym MAELIA stands for 'Modelling of socio-Agro-Ecological systems for Landscape Integrated Assessment'. Integrated assessment studies how the environment is affected by other sectors such as social, economic and agricultural sectors. It evaluates systems at varied spatial and temporal scales and examines how diverse stakeholders and decision-

makers' actions affect the system's behaviours. Integrated assessment unifies different sources, types of data and tools. MAELIA was launched in 2009 with the aim of developing a generic computer model to assess socio-economic and environmental impacts of agricultural and natural resource management practices at territorial scale. From a modelling and simulation perspective, the platform meets the challenge of representing a territory with a diversity of action situations. The platform processes spatial datasets to simulate spatiotemporal variations within an agricultural territory. MAELIA enables simulations at fine spatial (agricultural parcels and hydrological units) and temporal scales (daily scale). Socio-economic and environmental assessment indicators, such as gross and semi-net margins, agricultural yields, work volumes and peaks, and biophysical indicators (soil nitrogen and carbon levels, greenhouse gas balances) are produced at various temporal and spatial scales. Scenarios simulated with MAELIA are both evaluated quantitatively (analysis of output indicators) and qualitatively (verification of the compliance and accuracy of output spatiotemporal dynamics with local experts). MAELIA enables research, examines resource management scenarios for public organizations and facilitates exchanges with local stakeholders that aim to design new territorial organizations.

MAELIA is an information system formed by data pre and post processing modules and a multi-agent based model, whose implementation is based on the multi-agent based platform GAMA ("GAMA Platform | GAMA Platform," 2024). MAELIA is modular because hydraulic, biological, agroforestry, biodiversity, pasture, organic residue and methanization dynamics are coded into different programming modules that constitute extensions of the core multi-agent based agricultural programming module. Simulations that activate only certain modules can be run. The agricultural module is always active. The activation of modules is hard-coded in the main script of the multi-agent based model. Figure 3 describes MELIA's current agent-based modules and those under development (dvp = under development).

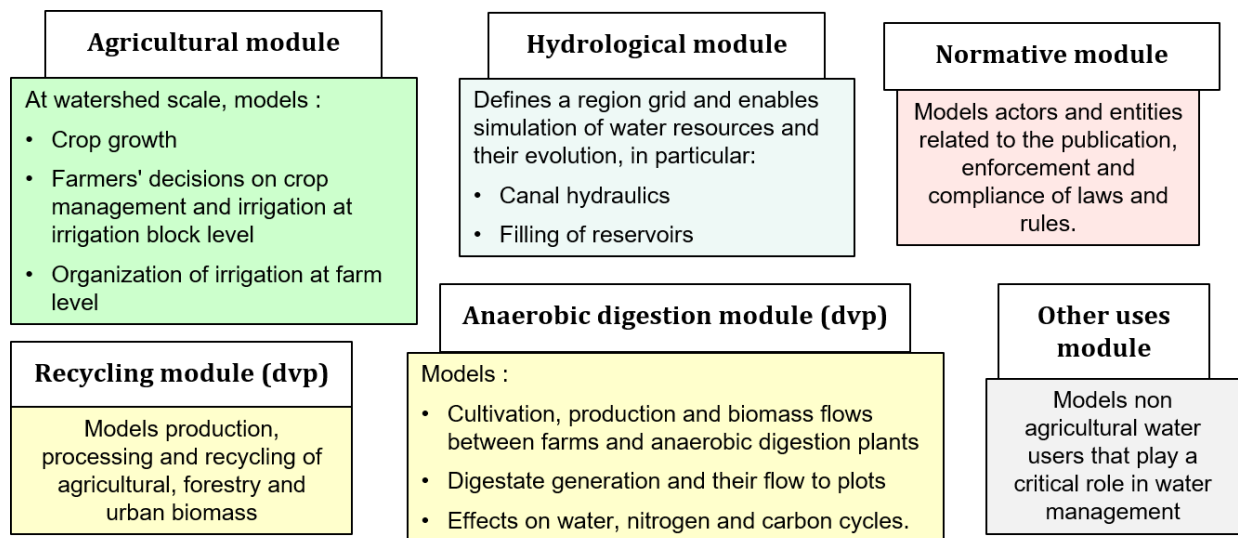


Figure 3: MAELIA's agent-based model modules

A detailed description of each of the four existing modules shown in Figure 3 is given in sections below together with a description of the economic module, which is not an extension of the agent-based model, but a compilation of R scripts that process output data from the multi-agent based simulations.

The activation of modules sets which agents are present in the multi-agent based model for each simulation. Each agricultural parcel is an instance of MAELIA. Case studies are built with stakeholders in three steps. The first step establishes a model of the current situation, the second step designs alternative territorial structures and management scenarios and the third step evaluates alternatives. An input data folder is associated to every scenario examined for a case study territory simulated with MAELIA.

The multi-agent architecture enables the simulation of territorial dynamics. The world is represented as a set of agents (soil agent, water agent, cereal agent, farmer agent, etc.), which communicate with each other and the environment in which they coexist. An Actor-Resource diagram (DAR), adapted to the description of socio-ecological systems (SES), is used to represent MAELIA's structure conceptually. The Actor-Resource diagram meta-model displays three classes of entities: actors, material and cognitive resources. Material resources symbolize tangible elements and cognitive resources elements that come into play in decision-making processes. The Unified Modelling Language (UML) is used to illustrate MAELIA's Actor-Resource diagram. Figure 4, translated to English from MAELIA's documentation website, shows the Actor-Resource diagram of a water police agent as an example of MAELIA's entire Actor-Resource diagram.

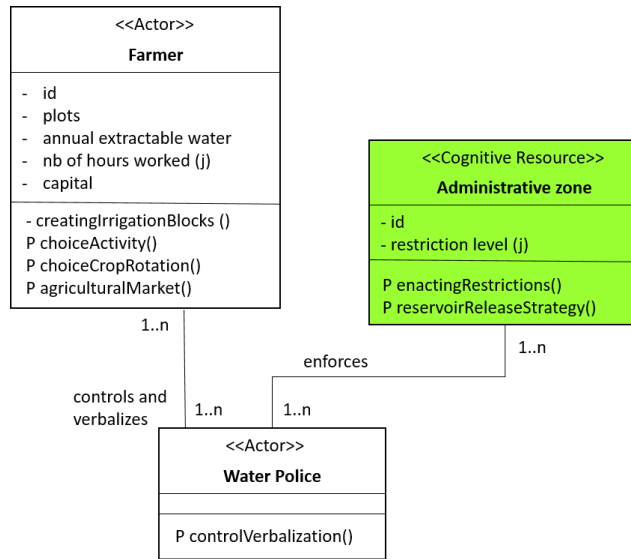


Figure 4: Actor-Resource diagram of a water police agent in MAELIA

A water police agent ensures that farmers comply with water restrictions and fines farmers that do not comply.

Activity diagrams illustrate scheduling blocks that orchestrate the simulations by indicating the order in which modules and modules’ entities are initialized. Scheduling blocks are launched at the beginning of the simulation, at the beginning of each simulated year and daily to handle variables’ updates.

b. Agricultural module

Table 1 lists entities of MAELIA’s agricultural module.

Table 1: Entities of MAELIA's agricultural module

Actors	Cognitive Resources	Material Resources
Farmer	Plots block Irrigation block Cultivated species Technical itinerary (ITK) Technical operation strategies <ul style="list-style-type: none"> - Hoeing strategy - Fertilization strategy - Harvest strategy - Return to work strategy - Seeding strategy - Irrigation strategy - Soil tillage strategy - Phytosanitary strategy Cropping system	Crop Farm Plot cluster Irrigation material Plot Withdrawal equipment - Irrigation Soil Meteorological zone

The only human actor modelled in the agricultural module is a farmer. Farmer agents in the agricultural module make decisions reactively and actively. They are involved in two decision-making processes. The first one involves choosing a crop rotation plan for cropping systems. The choice of crop rotation plan is done reactively because crop rotation plans for each agricultural parcel are given as input data. In MAELIA, a cropping system corresponds to the combination of a crop sequence (a loop of successive crops, e.g., corn/wheat/corn/canola) and a crop management strategy, named technical itinerary (ITK), which is a set of rules for managing a crop under a specific context. A plot context is defined by the last sown crop, soil type, farm type and irrigation equipment. For example, a corn technical itinerary might be irrigating corn using a center pivot on clayey soil downstream the Aveyron river for a crop sequence of irrigated corn/wheat. Farmers' second decision-making process involves an active choice of daily operational crop management operations, which depend on the selected strategic crop rotation plan. The order in which technical operations are carried out depends on a predefined priority order, on operation specific execution times, on meteorological conditions and on plots' spatial distribution. The predefined order of technical operations and the meteorological and temporal criteria that must be met for farmers to carry out technical operations have been established through surveys with farmers or agricultural experts. Decision rules that farmers follow for daily operational management of their technical operations have been translated into IF-THEN rules, which account for the decision context (regulations, past and future meteorological conditions, soil, plant and water states). If a technical operation cannot be carried out in a given initial time window, for example, due to unfavourable weather conditions, meteorological criteria can be relaxed and the time window for the technical operation can be extended. Decision rules

followed by farmers for daily technical operations are thus dynamically updated based on simulations' states and therefore agents make active operational decisions. Farmers make decisions at scales ranging from a plot, to a group of plots, to an irrigation block (a group of parcels with the same irrigation practices), to a farm.

MAELIA has two versions of the agricultural module: AqYield and AqYield-NC. The first version simulates crop growth and soil water dynamics. The second version simulates crop growth, soil water and nitrogen dynamics, organic matter mineralization and computes greenhouse gas (GHG) balances per plot. It also simulates soil carbon dynamics since nitrogen and carbon are intrinsically linked. Figure 5, translated to English from a course given by MAELIA's team, displays variables (in grey) and dynamics simulated by AqYield and AqYield-NC (elements outlined in yellow dashed lines are only included in AqYield-NC).

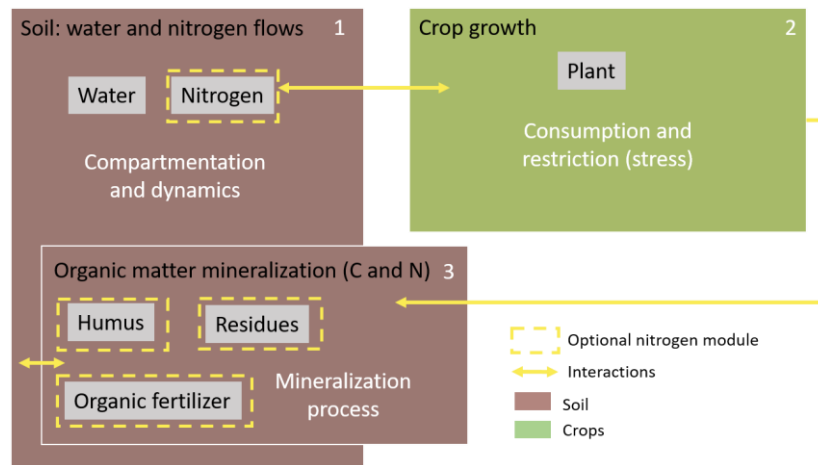


Figure 5: AqYield and AqYield-NC variables and simulated dynamics

AqYield-NC models the soil as four nested water reservoirs and four stacked nitrogen reservoirs. Plants draw water and nitrogen from these reservoirs to acquire water and nitrogen. The agricultural module simulates these processes. Water and nitrogen stress levels are estimated with water and nitrogen acquisition rates and enable the calculation of the agricultural yield. The stacking of nitrogen reservoirs is calculated based on the nesting of water reservoirs. Figure 6, translated to English from a course given by MAELIA's team, illustrates water and nitrogen reservoirs simulated by the agricultural module. RU stands for useful reservoir and HO for horizon.

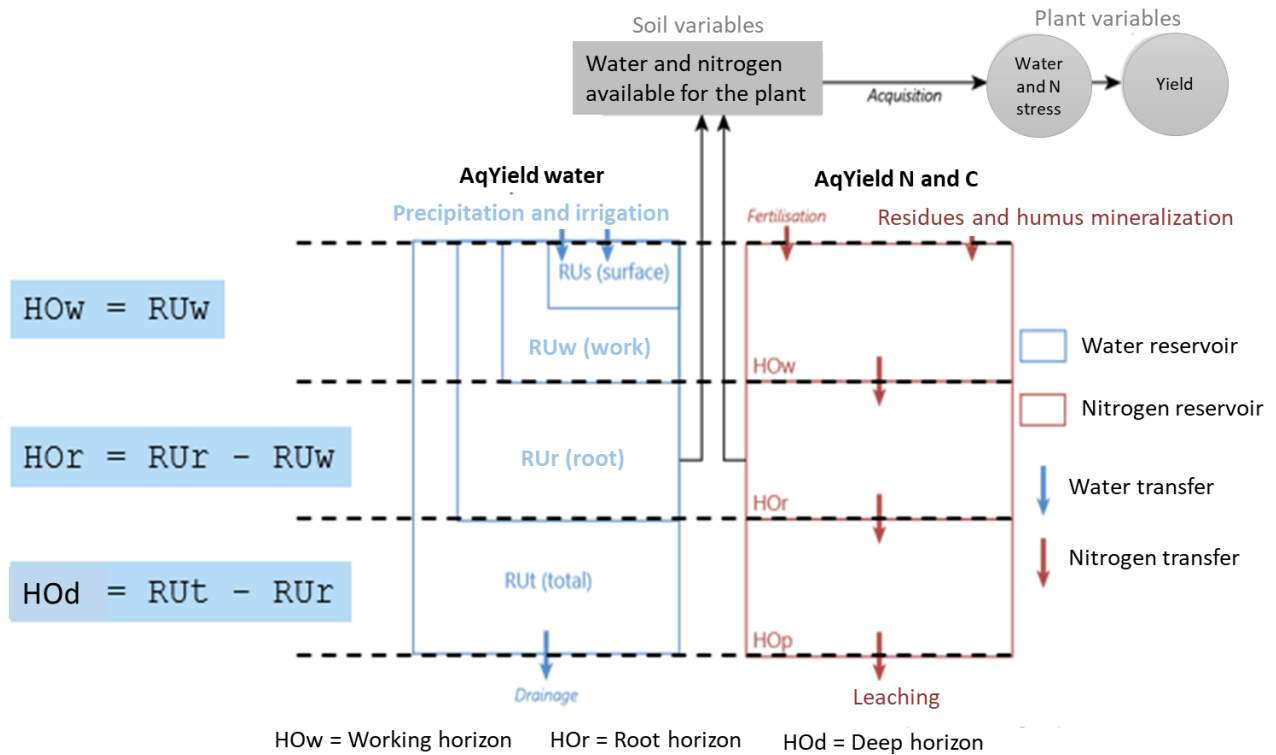


Figure 6: Water and nitrogen reservoirs modelled by MAELIA's agricultural module

The agricultural module simulates water transfers between compartments shown in Figure 6, as well as their filling and draining based on precipitation, irrigation and drainage. The first compartment is the surface water reserve, whose size evolves during the simulation between 8 mm and 30 cm and depends on soil tillage, rainfall, irrigation and soil clay content. The second reservoir is the working water reserve, with a fixed size of 30 cm. The third reservoir is the root water reserve, whose size depends on root growth and on soil's structural coefficient. Its minimum size is 30 cm; once a plant is sown, it has at least access to this reservoir's minimum size. The fourth reservoir is the total soil water reserve, whose size equals soil depth and whose clay and gravel rates are quantified. The depth and height of nitrogen reservoirs depend on those of the water reservoirs. Nitrogen working, root and deep horizons are defined. Nitrogen content in each horizon depends on water fluxes since water transports nitrogen from one horizon to another. Nitrogen is lost through leaching, gas emissions and plant uptake.

AqYield measures crop growth with a vegetation scale, that ranges from 0 at sowing to 1 at flowering. The vegetation scale is based on the sum of degree-days at flowering for each plant. Degree-days represent accumulated heat. Each crop accumulates degree-days at each simulation time step. A cultural coefficient is computed to estimate plants' water and nitrogen needs. It is calculated based on vegetation scale and on crop's photoperiodism, which induces that crop growth is slowed down in winter and thus reduces the water and nitrogen needs of the plant

during winter. The agricultural module quantifies soil water evaporation and plant transpiration. Quantifying plant transpiration enables the assessment of water stress experienced by plants, which influences their growth. Soil water evaporation is quite high in spring on bare soil; however, plant growth causes a slowdown and reduction in soil evaporation because water is taken and transpired by plants. Daily water stress experienced by a plant is deduced by comparing the plant's actual transpiration to its maximum transpiration. Total water stress experienced by a plant through its life cycle and the plant's maximum potential yield are used to compute the plant's final yield. A plant's maximum potential yield is estimated by field specialists.

AqYield-NC additionally simulates nitrogen and carbon dynamics. Plants' nitrogen demands are estimated based on their specific characteristics and the sum of degree-days over the simulation. Symbiotic nitrogen fixation by plants is estimated at the time of plant harvesting. The amount of nitrogen acquired by the plant is the minimum value between the plant's potential acquisition value and the quantity of nitrogen available in the working and root horizons; the plant does not have access to nitrogen in the deep horizon. Nitrogen plant stress is derived from the symbiotic fixation value. The stress value used to reduce a plant's maximum potential yield to obtain the final yield is the minimum value between water and nitrogen stress. Both stresses take values between 0 and 1, 0 indicates a lack of water or nitrogen experienced by the plant during its growth. Carbon dynamics are simulated through the modelling of soil organic matter, crop residues, mineral fertilization, organic residue products (PROs) and nitrogen losses. Nitrogen enters the soil through aboveground and root crop residues, mineral fertilization and organic residue products. Nitrogen exits the soil through NH₃ and N₂O emissions, plant uptake and nitrogen leaching. Figure 7, translated to English from a course given by MAELIA's team, illustrates these dynamics.

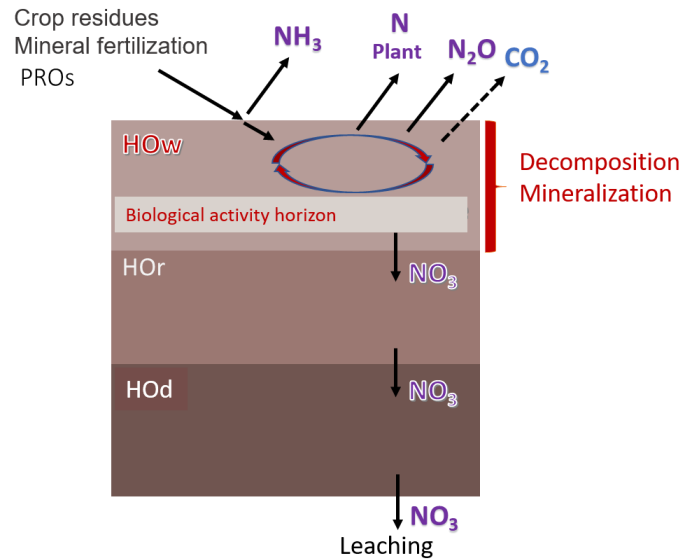


Figure 7: Nitrogen soil dynamics

For nitrogen to be available to plants, a portion of the organic nitrogen contained in residues and organic residue products (PROs) must mineralize. Organic matter is mineralized in the working horizon and mineralization is considered negligible deeper into the soil. The model assumes that as long as there has been no soil tillage after the application of aboveground residues and PROs, nitrogen available to plants remains unchanged. Therefore, in MAELIA's predefined order of crop management technical operations, soil tillage is planned after fertilizer application. The model simulates daily soil humus' decomposition and humification of aboveground residues, dead roots and PROs. Humus refers to soil's organic matter, including dead organic matter from plants, animals, fungi and bacteria. Humus decomposition depends on organic carbon and nitrogen stocks present in the soil, on the availability of active and inert pools of decomposed organic matter, on air and soil temperatures, soil moisture, clay and limestone contents and on pH. Within an organic matter pool, there are different stages of decomposition. The agricultural module assumes that after one year, all organic nitrogen has mineralized. The module incorporates formalisms and equations from various existing models (AMG, INDIGO, SystN-STICS and STICS) to quantify nitrogen losses and compute greenhouse gas (GHG) balances. CO2 equivalents are used to quantify GHGs related to nitrogen emissions. The GHG balance measures direct N2O losses, indirect losses (NO3 and NH3), nitrogen plant uptake, GHGs emitted from fertilizer synthesis (estimated using GESTIM+ model) and soil organic carbon storage. Seeds' GHG emissions are not considered.

c. Hydrological module

Table 2 lists MAELIA’s hydrological module’s entities. It does not have actor or cognitive resource entities, since the module only simulates interactions between material resources.

Table 2: Entities of MAELIA's hydrological module

Actors	Cognitive Resources	Material Resources
		Dam Withdrawal equipment – Canal Discharge equipment – Canal HRU (Hydrologic Response Unit) Water reserve <ul style="list-style-type: none"> - Canal - Watercourse - Water table - Dam Soil Elementary watershed Meteorological zone

MAELIA’s hydrological module is an adaptation of SWAT (“SWAT | Soil & Water Assessment Tool,” 2024), which models water dynamics within and between water resources. The module simulates rivers, hillside reservoirs, aquifers and soils’ water dynamics. SWAT is semi-distributed and spatially explicit. An elementary sub-watershed is the main hydrological entity processed by SWAT and a Hydrologic Response Unit (HRU) is an elementary sub-watershed area considered hydrologically homogeneous. An HRU corresponds to the intersection of a land cover type, a soil type and a range of slope values. SWAT models three phases of water dynamics: snow, soil and routing phases. The snow phase simulates rain/snow partitioning and snowmelt, the soil phase models soils’ water flows and the routing phase simulates rivers’ water flows. The snow phase is optional, and if activated, the hydrological model begins by computing snow phase, followed by soil and routing phase calculations. Pollutant and suspended matter fluxes are also simulated. Figure 8, translated to English from a course given by MAELIA’s team, illustrates flows simulated by the soil phase of the hydrological module.

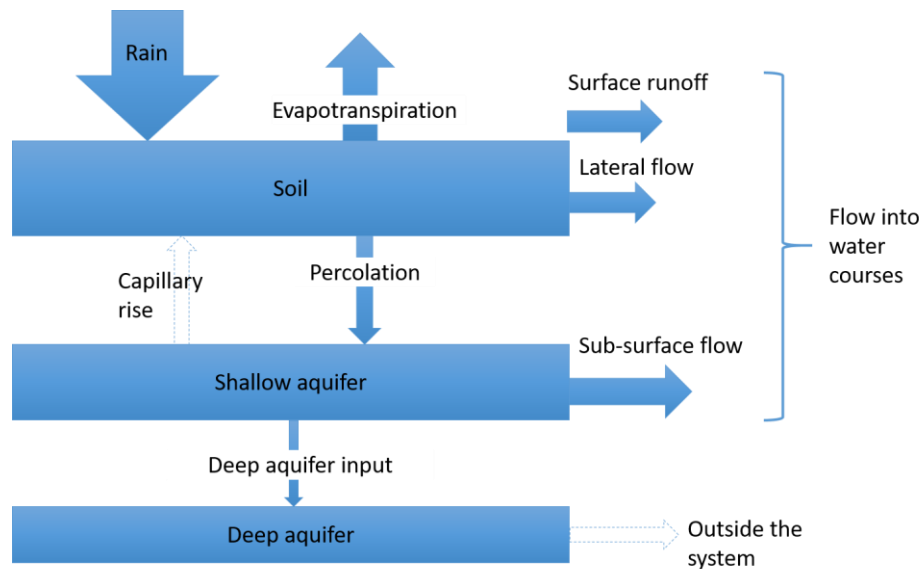


Figure 8: Flows simulated by the soil phase of MAELIA's hydrological module

As illustrated in Figure 8, the soil phase calculates rain infiltration, soil moisture content, surface runoff, lateral flow, evaporation and transpiration, percolation to the shallow aquifer and discharge from the aquifer to streams (sub-surface flow) and to the deep aquifer. The deep aquifer is not modelled. The routing phase calculates watercourses' states and water volumes that flow outside the studied watershed. Routing phase calculations are run after accounting for daily volumes of water extracted by actors of the multi-agent based model. Soil phase calculations are done at HRU (Hydrologic Response Unit) level. For instance, the total runoff of an elementary watershed equals the sum of the elementary watershed's HRUs' runoffs. For French case studies, the CORINE Land Cover database is used to demarcate HRUs and agricultural HRUs (HRUs covered with agricultural land) are identified with Parcel Graphical Register's data. The agricultural module is in charge of computing evapotranspiration, runoff and percolation of agricultural HRUs and passes this data to the hydrological module. Meadows are currently managed by SWAT but will be managed by a meadow model in the near future. Non-agricultural HRUs are entirely managed by MAELIA's hydrological module. Temperature and precipitation values obtained from national meteorological data sources are adjusted with altitude values, if the snow phase is activated. If the average air temperature is strictly below -0.5°C , the module considers snow precipitations. Fractions of HRUs covered by snow are empirically calculated based on snow temperature.

SWAT calculates surface runoff and infiltration using the "Curve Numbers" empirical approach. The Curve Number is an empirical parameter indicating soil's potential runoff. Soil moisture and slope modulate the "Curve Numbers." If the soil moisture content is higher than the field capacity, there is percolation and lateral flow. Field capacity corresponds to the maximum water volume a soil can hold in its porosity. Kinematic storage conceptual model is used to model lateral

flows. The routing phase calculates watercourses flows' with the Muskingum Routing method. Transmission losses to the soil and losses to the shallow aquifer are neglected by the routing phase. Floodplain is not modelled.

Channels are simulated if they transfer water between elementary watersheds or if they serve as resources for water withdrawals. French reservoirs are referenced with data from the BD TOPO database ("BD TOPO® | Géoservices," 2021). Volumes, hydrological characteristics and uses of reservoirs are derived from declarations made to governmental entities or estimated through GIS (Geographic Information System) processing. Four types of hill reservoirs are represented to model the availability of water resources for irrigation and the impact water extraction dynamics have on hydrology. These are aquifer reservoirs (always considered filled if the aquifer is not empty), reservoirs connected to main rivers (filled by the main river, runoff and later flows), reservoirs connected to secondary rivers (filled by runoff and later flows), and reservoirs disconnected from rivers resulting from runoff. Water exits reservoirs through evaporation, reserved flow, if the reservoirs are connected to a main river, withdrawals and overflow. Water law mandates a reserved flow to ensure that the main river maintains a minimum flow.

d. Normative module

The normative module simulates the implementation and compliance control of laws and rules related to agricultural water uses. Table 3 lists MAELIA's normative module's entities. The module models four types of actors: prefects, dam managers, a water police agent and a French organism named "Unique organisation for collective management" in charge of managing irrigation water allocations for an entire watershed. The prefect issues restriction orders and takes decisions regarding dam water releases to support low-flow periods. Dam managers carry out water releases. The water police agent monitors and penalizes farmers who do not comply with water usage restrictions during low-flow periods. It also annually inspects farmers who have extracted more water than the volume the unique organization for collective management has allocated to them.

Table 3: Entities of MAELIA's normative module

Actors	Cognitive Resources	Material Resources
Dam manager Unique organisation for collective management Water Police Prefect	Administrative sector Measurement station Administrative zone	Management unit

Dams do not appear as a resource in Table 3 because, from a hydrological standpoint, there is no difference between a reservoir and a dam, and a dam is already a hydrological module entity. The difference lies in the management; a dam is a reservoir managed to release water at critical times. Dams are modelled in MAELIA to represent low-flow support releases. Hydroelectric dam releases are not represented as EDF (“Electricité de France”, the main french energy company) does not share information on water releases for electricity production. Low-flow periods are times when river flows are particularly low. Water is released from dams to maintain river flows that enable to meet user’s needs during low-flow periods. Water released from dams goes into rivers of the elementary watersheds up to the nodal point where rivers of the watershed converge. Changing release patterns typically requires manual intervention for most dams and patterns are modified once or twice a week at most. When the dam volumes fall below a certain threshold, questions arise about the timing of water releases. The normative module simulates a priority order between dams based on water releases’ costs. The normative module assumes that upstream dams are full on January 1st of each year. The hydrological module simulates the filling of dams and reservoirs. The low-flow target flow measured at the nodal points of a watershed is a reference flow that ensures ecosystem health and that water needs of all users are satisfied on average eight out of ten years. Dam management is coded as a set of IF-THEN rules in MAELIA. To establish volumes released by each dam, the prefect estimates water needs of a river by taking the difference between the low-flow target and the flow measured at the corresponding measuring station. If the flow to be released is greater than the critical flow of a priority dam, then the remaining flow is released by the next dam that can ensure this release. The flow is considered critical if the volume of the dam is below the critical volume. The normative module defines administrative zones and sectors to manage irrigation restrictions. Administrative sectors are zones defined within an administrative zone to alternate restrictions. For example, for sectors A and B in the same administrative zone, sector A is allowed to carry out withdrawals on Mondays, Tuesdays and Thursdays and sector B on the remaining week days. Regulatory thresholds other than the low-flow target are introduced in MAELIA and restriction levels are defined in relation to these thresholds. Each administrative zone is assigned a restriction level and the prefect is responsible for updating the restriction rules. Based on the number of days since the last order, the prefect can increase or decrease the restriction level for each zone. Additionally, the prefect is responsible for maintaining upstream-downstream consistency in the watershed, meaning there cannot be more than one level of restriction difference between two restriction zones located upstream and downstream of the basin. MAELIA also allows simplifying restriction rules by assigning a restriction level to a flow value. The user can modify the corresponding values by editing an input file. The platform represents three special cases. The first one are non-refilled zones, which are watersheds with autonomous hydrology. The main rivers of the zone originate within the zone, and there are no low-flow support releases or nodal points, but restrictions are still simulated in the zone. The flow

considered to establish restrictions is the median flow of elementary watershed flows measured in the zone. Restrictions are established by administrative zones and for each type of watercourse. The second special case are canals. Restriction levels established to fill canals correspond to restriction levels of the canal’s administrative zone. MAELIA simulates the closure of gates at the end of the canal. The third special case are derogatory crops for which water withdrawals may take place despite restrictions.

e. Other uses module

The "Other Uses" module simulates water uses for non-agricultural purposes, such as withdrawals and discharges of water for domestic and industrial purposes. Table 4 list entities of MAELIA’s "Other Uses" module.

Table 4: Entities of MAELIA's "other uses" module

Actors	Cognitive Resources	Material Resources
Municipality Industry		Equipment Withdrawal equipment For domestic use For industrial use Discharge equipment For domestic use For industrial use

The "municipality" actor is represented because drinking water consumption and wastewater discharges of domestic users are calculated at municipal level. The "heavy industry" actor is also included in this module to simulate industrial water consumption and wastewater discharges.

f. Economic module

The economic module is different from the modules described above because it is not an extension of MAELIA's multi-agent based model, but a set of R scripts that process outputs from MAELIA’s simulations and that are integrated into a workflow that computes output indicators. It has been developed in collaboration with ARVALIS (“ARVALIS, institut technique agricole grandes cultures et fourrages,” 2024). Economic indicators are produced at parcel level. Several crop selling prices scenarios are simulated. Price scenarios are based on observed or projected data. Observed prices are shared as public open data and year 2015 is taken as a reference for the consumer price index. Price projections are made based on the Shared Socio-economic Pathways (SSP) scenarios and by adding noise and varying inflation rates. SSP scenarios are new climate scenarios projected by the Intergovernmental Panel on Climate Change (IPCC), which describe different socio-economic development pathways in relation to various predicted

greenhouse gas emission trajectories. Output economic indicators include gross and semi-net margins. Equation 1 details calculations of the semi-net margin.

Equation 1: Agricultural semi net margin

Agricultural semi net margin [€] = Income [€] – Costs [€], where :

Income [€] = Crop selling prices [€/ha]. Yield [ha] + Subsidy [€]

Costs [€] = Fertilizer [€] + Phytosanitary [€] + Fuel [€] + Water [€] + Workfoce [€], with :

Water [€] = Irrigation costs [€] + Water taxes [€]

To obtain a net margin, equipment's' investments cost need to be considered. To obtain gross margins subsidies and labour costs are ignored.

g. Sum up and planned extension

To conclude, MAELIA is a generic integrated multi-agent based platform that simulates agricultural scenarios designed with local stakeholders. It simulates farmers' daily and strategic decision-making processes as well as regional water managers' restriction actions. Simulating systems at operational and strategic decision levels is recommended by (Martinez-Hernandez et al., 2017) to assist in medium and long-term decision-making. The tool is spatially explicit and enables spatial visualization and analysis of the simulations. The platform is modular and combines a multi-agent based model with dynamic biophysical and hydrological simulation modules. The integration of dynamic biophysical models is rare but also recommended to simulate water-energy-food nexus systems (Martinez-Hernandez et al., 2017). The agricultural module is always activated since the platform is designed to simulate agricultural landscapes and processes and hydrological, normative and other modules under development are optional. This modular construction makes the platform generic, as recommended in the literature (Martinez-Hernandez et al., 2017). MAELIA enables the simulation of groups and sub-groups of agents acting at distinct temporal and spatial scales, conceptualizing different levels of action (Vo, 2012). The scope and variety of physical entities and actor agents represented by the multi-agent based model varies for each simulation according to the activated simulation modules. One core strength of the collaboration with MAELIA is that it adopts a participatory approach, as recommended by the PSE community (Gerbaud, 2023), since its developers work in collaboration with agricultural stakeholders to define realistic scenarios that are in line with farmers' objectives and respect their habits. MAELIA is applied to local and regional nexus systems (e.g., the Aveyron watershed with a total area of 800 km²) over periods of ten to fifteen years.

We have therefore selected MAELIA, which has already given rise to numerous studies around the water-food nexus, as the multi-agent based platform for our multi-actor multi-level

framework. MAELIA enables simulating the water-food nexus of our case study territory at operational temporal and spatial scales. Moreover, we wish to contribute to its extension to enable the platform to simulate complete water-energy-food nexus systems. The extension aims at broadening the platform's model and functionalities to incorporate the simulation of energy resources and water-energy and energy-food links to obtain a platform that simulates complete water-energy-food nexus systems in agricultural land at operational scales.

Our contribution to the extension of MAELIA is twofold:

1. The adaptation of MAELIA's multi-agent based SES model to enable the simulation of solar panels and wind turbines in agricultural land and their impact on water and food systems (Chapter 5 of this manuscript).
2. The development of strategic multi-actor decision-making methods that rely on operational data produced by MAELIA to design optimized scenarios of renewable energy generation units allocations in agricultural land that are accepted by all actors of the system (Chapters 3 and 4 of this manuscript).

The next section presents the methodologies conceptualized to lead agricultural land suitability studies for solar panels and wind turbines.

III. Agricultural land suitability study for solar panels and wind turbines

a. Introduction

This paragraph explains the methodology developed to identify agricultural land that is suitable for solar panels and wind turbines. QGIS and pyQGIS are used. This step is crucial to simulate and evaluate scenarios of renewable energy generation units' allocations in agricultural land that are geographically feasible and comply with regulations.

b. Suitability study for solar panels

i. Process conceptualization

Regulations and literature on ground-mounted photovoltaic installations do not provide standard technical criteria regarding the suitability of agricultural land. It is recommended to select a flat, clear, easily accessible ground, that covers several hectares and accounts with a current transformer nearby (Ministère de l'Écologie, du Développement durable, des Transports et du Logement, 2011). The methodology applied to evaluate the suitability of agricultural land for ground-mounted photovoltaic installations in this work has been inspired by literature on roof photovoltaics. Literature recommendations concern orientation and inclination of panels. It

advises against north (0/360°), northeast (45°) and northwest (315°) orientations, and against inclinations greater than 60° (Wallon, 2021). The resulting process is the following:

1. Excluding plot areas with exposure in between 0 and 45° and 315° and 360°.
2. Excluding plot areas with a slope greater than 60°.

Shade has not been selected as a suitability criterion for ground-mounted photovoltaic panels, because even though it reduces panel efficiency, it does not prevent energy production. Shade is nonetheless integrated into this work because it directly impacts the recorded sunlight value, which is used to estimate panels' energy production. Sunlight data corresponds to solar radiation incident on a surface. At sizing of the photovoltaic installations, compliance with the urban planning code and legislation are considered. Compliance with safety distances to roads, residences, etc., is included in the estimation of panels' ground footprint, which is used to compute the maximum number of panels per plot.

ii. Process implementation

Figure 9 illustrates the implementation of the process conceptualized to identify plots areas that are suitable for ground-mounted photovoltaics.

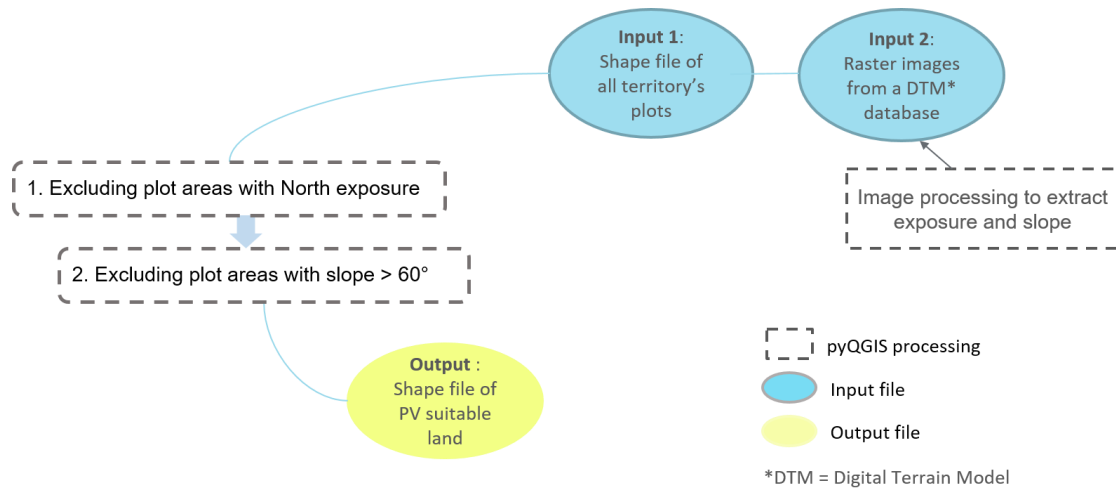


Figure 9: Process to identify suitable land for ground-mounted photovoltaics

Flowchart in Figure 10 provides a more detailed overview of the computer program developed.

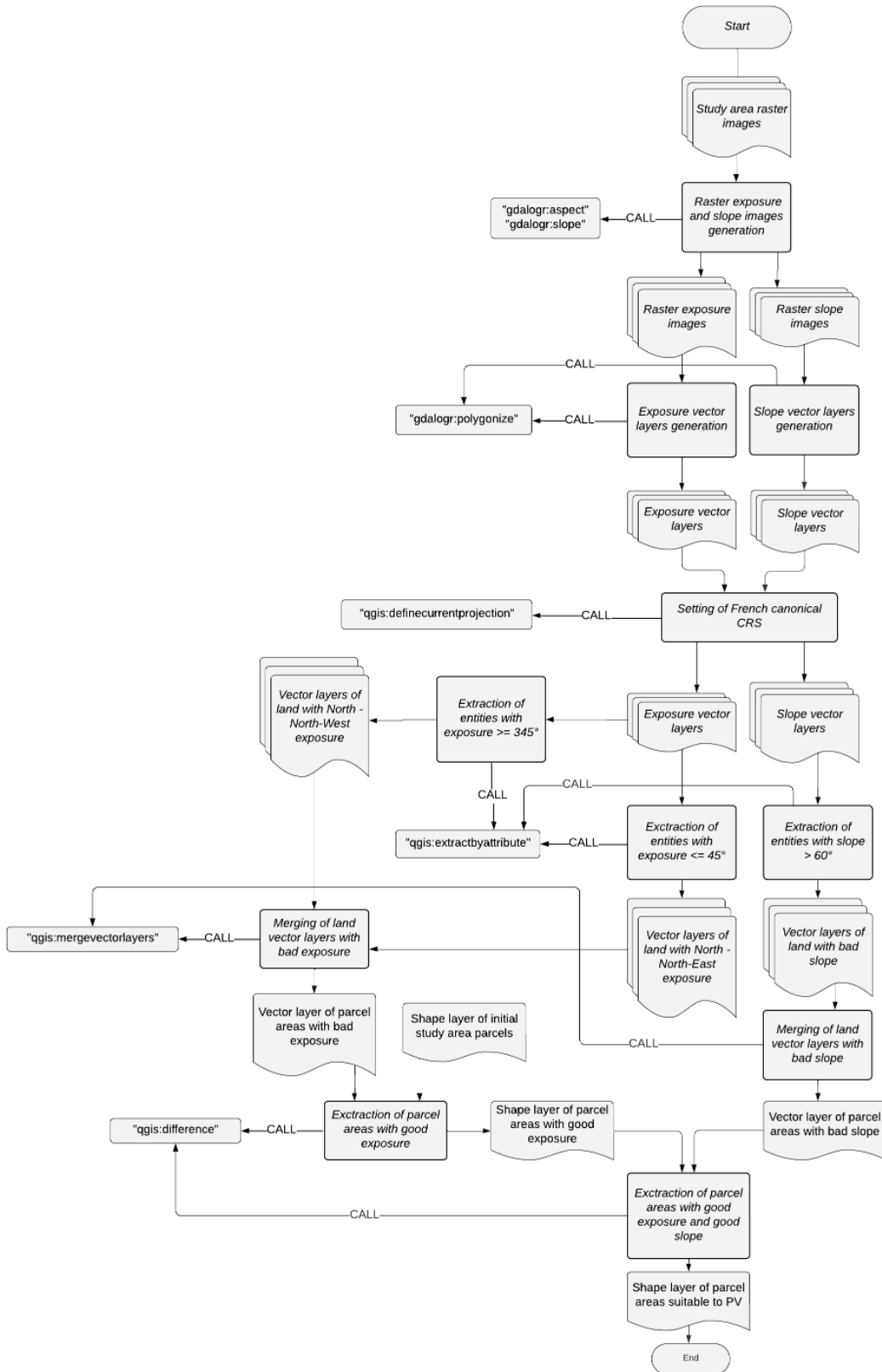


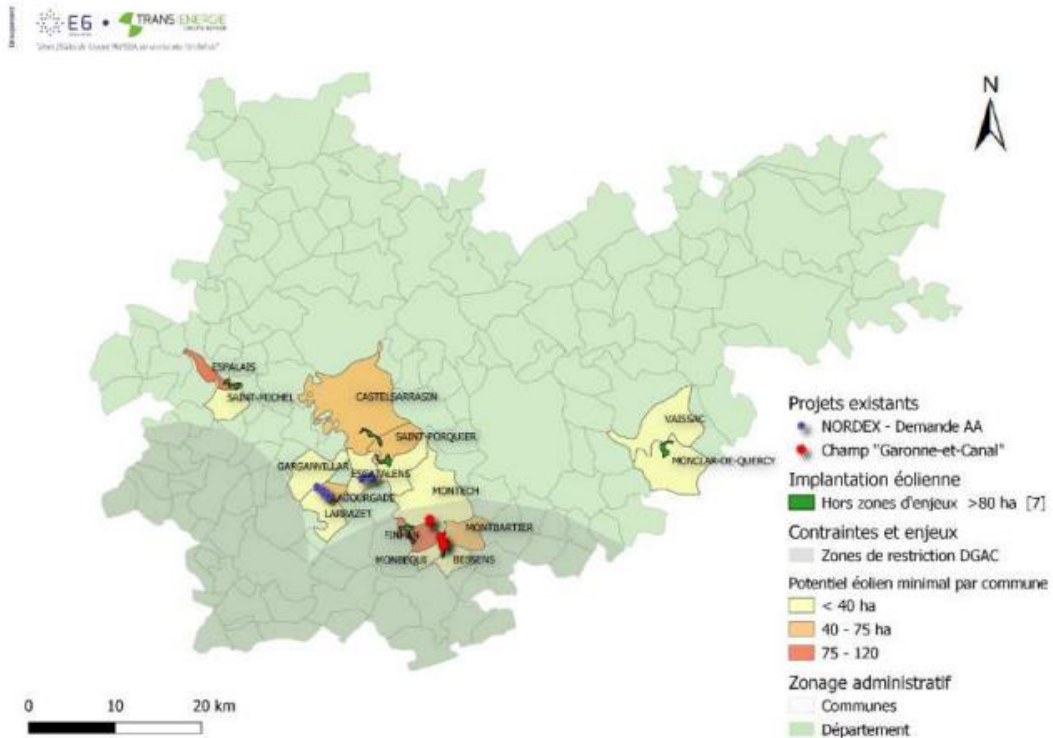
Figure 10: Flowchart of the computer program developed to identify land suitable for ground-mounted photovoltaics

Flowchart in Figure 10 shows that the first step of the computer program developed to identify suitable land for ground-mounted photovoltaics involves retrieving raster images from a digital terrain model. For French case studies the digital terrain model used is BD ALTI (“BD ALTI® | Géoservices,” n.d.), which is produced by the French National Institute of Geographic and Forestry Information. To identify raster images of the case study area, raster images of the departments covered by the study area are overlaid on the parcels layer of the study area with QGIS. The next step involves deriving exposure and slope raster images from the original raster images using functionalities from QGIS’ raster terrain analysis tool (“Raster Terrain Analysis Plugin,” n.d.), and more precisely by calling the "aspect" and "slope" functions of the GDAL/OGR geo-processing library. To apply numeric filters to exposures and slopes, exposure and slope raster images are transformed to vector exposure and slope layers by calling the 'polygonize (Raster to Vector)' function of the GDAL/OGR geo-processing library in QGIS. Coordinate reference systems (CRS) of the new vector layers are set equal to that of the study area’s plots layer, i.e., Lambert 93 (EPSG:2154), which is France’s standard CRS (“Les Systèmes de Coordonnées de Références — Documentation Briques de Géomatique 0.1,” n.d.). To eliminate areas with bad exposures, exposure vector layers of parcel areas with exposure values smaller than 45° and bigger than 315° are created using QGIS’s geo-processing function 'extractbyattribute' from the Python console. These exposure vector layers are merged into a single vector layer of badly exposed areas using QGIS’s geo-processing function 'mergevectorlayers'. The difference between the resulting layer and the layer of the study area’s initial plots is then performed using QGIS’s 'difference' function, called from the Python console. A shape layer of plots with good exposures is obtained. Similarly, the computation of the vector layer of areas with bad slopes is done and this layer is used together with the shape layer of plots with good exposures to derive the final shape layer of plots with good exposures and slopes.

b. Suitability study for wind turbines

i. Process conceptualization

In France, the II Grenelle law of 2010 established that each region must produce a document that indicates suitable zones for wind power development. These zones must be defined in line with European energy and climate objectives. Retrieving these documents is the first step of the process conceptualized to identify agricultural land suitable for wind turbines. For example, MAELIA’s study area located downstream the Aveyron’s watershed lies entirely within the Occitanie region and covers the Lot (46), Tarn (81) and Tarn and Garonne (82) departments. Maps of favourable zones for wind power development in these departments are available on the DREAL (Regional Department for the Environment, Planning and Housing in Occitanie) website in pdf format (Occitanie, 2021). For instance, Figure 11 shows the Tarn and Garonne (82) map.



NB : Les cartes de potentiel font apparaître un projet en cours d'instruction sur les communes de Labourgade et Cordes-Tolosannes dont l'instruction a été suspendue depuis du fait de l'évolution des servitudes aéronautiques et de défense.

Figure 11: Map showing suitable Tarn and Garonne zones for wind turbines

Studies issuing these maps consider residential areas, radar protection zones, areas protected by civil aviation authorities, landscape, heritage, bird and chiropteran concerns, as well as territory's relief. Favourable communities for wind energy development are identified by overlaying these maps to case study agricultural areas.

The second step consists in identifying agricultural plots located in zones declared suitable for wind energy development by regional authorities that comply with safety distances imposed and recommended by legislation. Table 5 summarizes entities concerned by these safety distances, values of the associated safety perimeters and data sources to locate entities for French territories.

Table 5: Safety perimeters that wind turbines must comply with

Entity	Safety perimeter	Data source
Power lines	If voltage = 400 kV, buffer zone radius = 188,10 m If voltage = 225kV or 63 k, buffer zone radius = 168,5m (Christophe Leblanc, 2015)	BD CARTO v5 - TOUS THEMES from IGN: n°dept \EQUIPEMENT\LIGNE_ELECTRIQUE.shp
Aerodromes	-	BD CARTO v5 - TOUS THEMES from IGN: n°dept \EQUIPEMENT\AERODROME.shp
Railroads	Buffer zone radius = 200 m (Elisabeth Borne and Emmanuelle Wargon, 2019)	BD CARTO v5 - TOUS THEMES from IGN: n°dept \RESEAU_FERRE\TRONCON_VOIE_FERREE.shp
Residential zones	Buffer zone radius = 500 m (Elisabeth Borne and Emmanuelle Wargon, 2019)	BD CARTO v5 - TOUS THEMES from IGN: n°dept \LIEUX_NOMMES\ZONE_D_HABITATION.shp
Park or nature reserve	-	BD CARTO v5 - TOUS THEMES from IGN: n°dept \ZONES_REGLEMENTEES\PARC_OU_RESERVE.shp
Plant formations	-	BD FORET from IGN: n°dept \FORMATION_VEGETALE.shp

The resulting process for determining the suitability of agricultural land for wind turbines is as follows:

1. Identification of areas suitable for wind farm development based on regional studies, in France:
 - Identification of departments concerned by the study area
 - Identification of departmental areas suitable for wind power development
2. Consideration of technical safety distances with the following entities:
 - Power lines
 - Aerodromes
 - Railroads
 - Residential areas
 - Parks or nature reserves
 - Plant formations

ii. Process implementation

Figures 12 and 13 illustrate the implementation of the process conceptualized to identify areas of agricultural parcels suitable for wind turbines. Figure 12 shows the first part of the process.

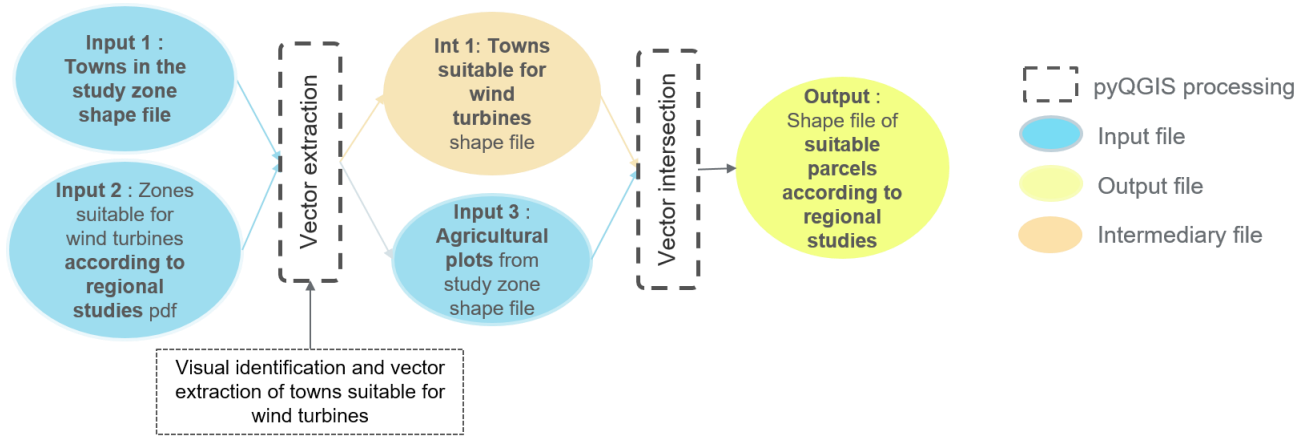


Figure 12: Implementation of the identification of areas suitable for wind turbines based on regional studies

Figure 13 shows the second part of the process.

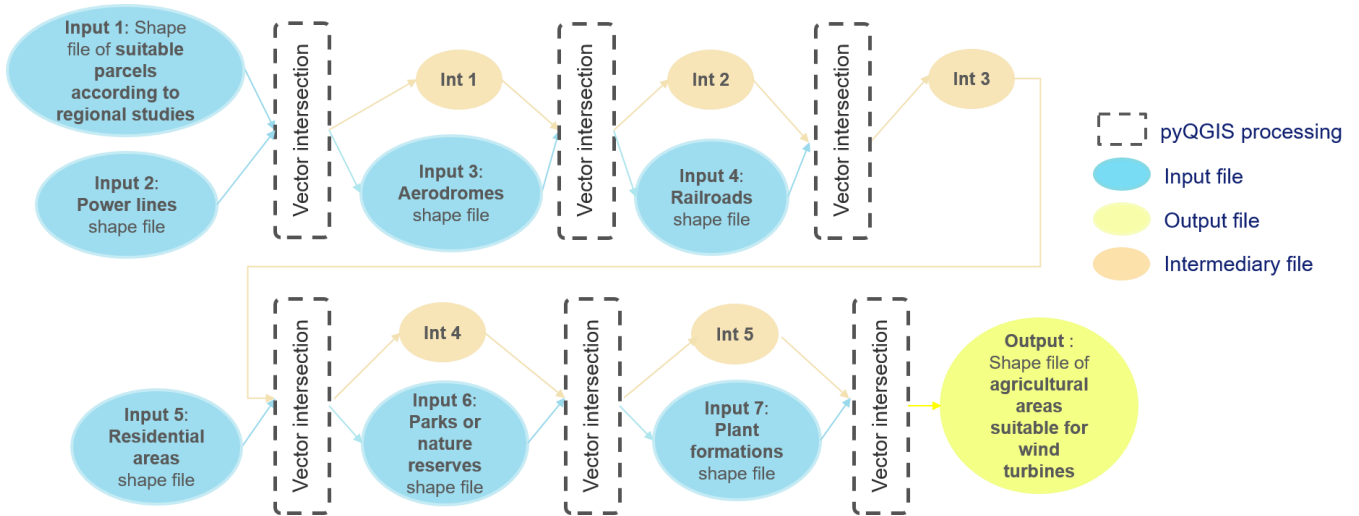


Figure 13: Implementation of the consideration of technical safety distances with geospatial entities

Flowchart in Figure 14 provides a more detailed overview of the computer program developed.

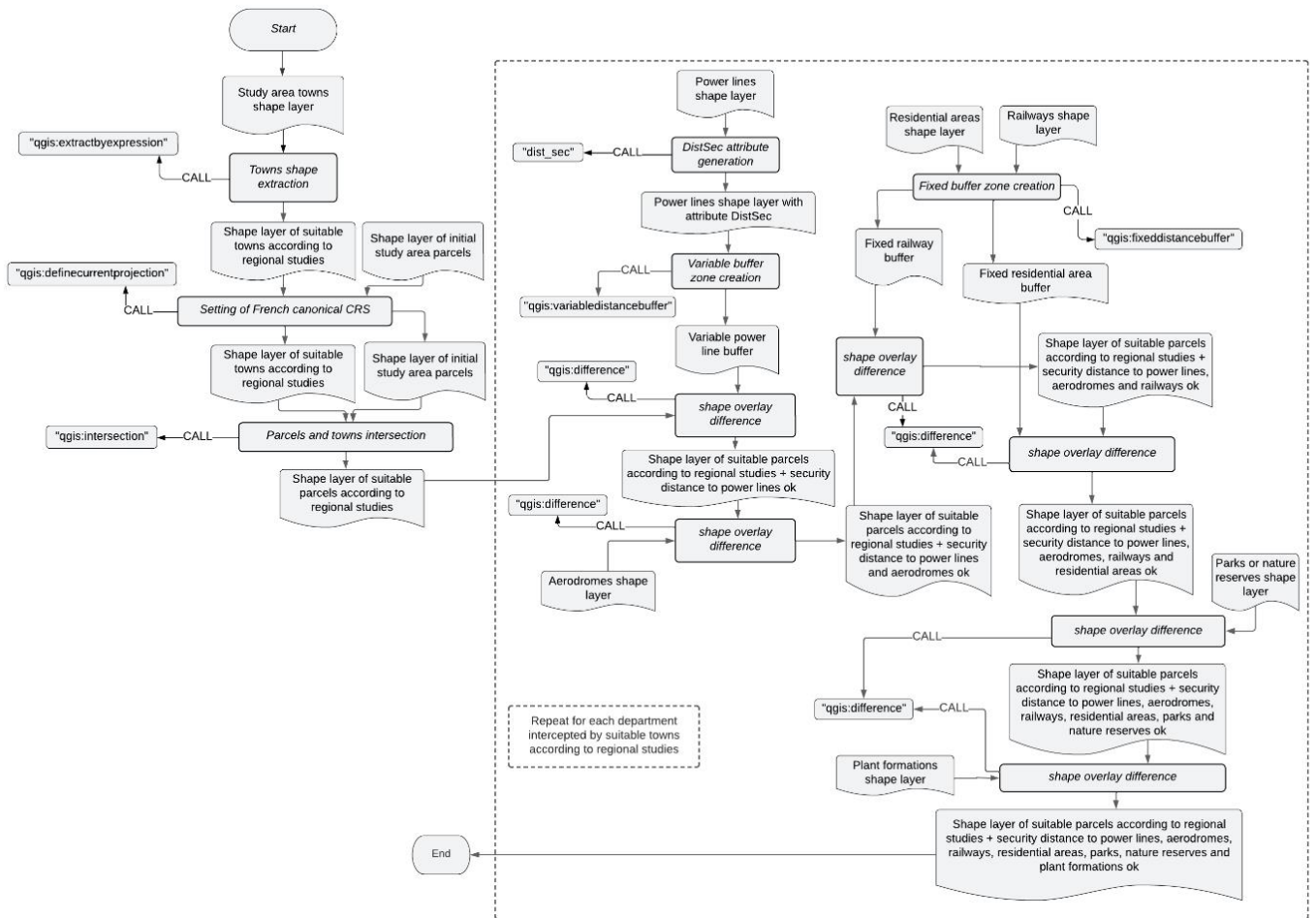


Figure 14: Flowchart of the computer program developed to identify land suitable for wind turbines

The first step consists in creating a shape layer of study zone towns declared suitable for wind turbines by regional studies from the initial shape file of all study zone's towns. Qgis' geo-processing function "extractbyexpression" is called from QGIS' python console. For MAELIA's case study area located downstream the Aveyron river, the expression used is: ""CODE_INSEE" = '82184' OR "CODE_INSEE" = '82115'", as these identifiers correspond to Vaïssac and Monclar-de-Quercy towns respectively, which are the two case study towns declared suitable by regional studies. The CRS of this new shape layer and of the shape layer containing the study zone's initial plots are set equal to the French canonical CRS. Then, an interception between these two layers is performed to obtain a shape layer of plots located in towns declared suitable for wind turbines. This is done with qgis' geo-processing function "intersection", called from the python console. Afterwards, for French case study zones, a six-step process is repeated for each department intercepted by suitable towns since the French National Institute of Geographic and Forestry Information shares departmental data layers. The first step of the six-step process is to add an attribute to the power line shape layer with a personal function created with pyQGIS, which associates a safety distance of 188.8 m for 400 kV voltages and equal to 168.5 m for other

voltages. Next, a variable distance buffer shape layer is created from this new attribute. This step is performed using the "variabledistancebuffer" qgis geo-processing function, called from the python console. Finally, the first step is completed by doing the difference between the power lines buffer vector layer and the vector layer of suitable agricultural plots according to regional studies. This step is performed using Qgis' geo-processing function "difference" called from the python console. The second step performs the difference between the last shape layer created and the aerodromes shape layer. A shape layer of suitable parcel areas according to regional studies that respect security distances with power lines and aerodromes is obtained. The third step starts by creating a railroads buffer vector layer with a 200 m radius, using Qgis' geo-processing function "fixeddistancebuffer" called from the python console. Then it performs the difference between the last shape layer created and the railroads buffer layer to obtain a shape layer of suitable parcel areas according to regional studies that respect security distances with power lines, aerodromes and railroads. The fourth step starts by creating a 500 m radius residential areas buffer layer and makes the difference between the last plots shape layer created and this buffer layer to obtain a shape layer of suitable parcel areas according to regional studies that respect security distances with power lines, aerodromes, railroads and residential areas. The fifth step computes the difference between the last plot layer created and the parks and nature reserves shape layer to obtain a shape layer of suitable parcel areas according to regional studies that respect security distances with power lines, aerodromes, railroads, residential areas and parks and nature reserves. The sixth and last step computes the difference between the last plot layer created and the plant formations shape layer to obtain a shape layer of suitable parcel areas according to regional studies that respect security distances with power lines, aerodromes, railroads, residential areas, parks and nature reserves and plant formations.

c. Conclusion

This paragraph has explained the methodologies conceptualized to identify agricultural land that is suitable for solar panels and wind turbines as well as how they are implemented for French case study zones. QGIS, pyQGIS and public data produced by the French National Institute of Geographic and Forestry Information are used to implement the processes. The next section presents the multi-criteria indicators selected and designed to evaluate water-energy-food nexus systems from multi-sector and multi-actor perspectives. These are used to develop strategic multi-actor decision-making methods needed for our multi-actor multi-level framework.

IV. Multi-actor multi-sector indicators to evaluate WEFN scenarios

a. Introduction

This section presents multi-actor multi-sector indicators selected and developed to characterize water-energy-food nexus systems in agricultural land. The following resource production and

consumption, environmental, economic and social indicators are used to compare the state of water-food-energy systems under different scenarios. They are not intended to serve as indicators of the precise environmental, economic or social state of the systems. The objective is to feed them to strategic decision-making methods that produce optimized resource management scenarios accepted by all actors of the system.

b. Overview

The indicators have been chosen according to the water-food-energy nexus literature that incites studies to evaluate water-energy-food systems in terms of sustainability, resilience and synergy (Giampietro et al., 2013). Sustainability characterizes a system’s capacity to satisfy its present needs without jeopardizing its ability to satisfy its future needs. Indicators of sustainability are those that measure resources’ availability and accessibility, resources’ security, as well as the feasibility, viability and desirability of management solutions. Indicators of resilience characterize the system’s capacity to ensure the provision of the system functions in the face of shocks and stresses (Dardonville et al., 2021; Meuwissen et al., 2019). Synergy indicators evaluate the degree to which interactions and trade-offs among resources are considered. The evaluations of the above criteria are considered complete if the indicators address all three economic, environmental and social dimensions.

Indicators developed to characterize WEFN systems’ states are summarized in Table 6.

Table 6: Multi-criteria indicators to characterize the sustainability of water-food-energy nexus systems

Indicators	Energy	Water	Food
Resource production and consumption	Renewable integrated energy production [J]	Water withdrawal indicator (Irrigation water volume * Water origin integer)	Integrated caloric [J] and protein [kg] yields of crops
Economic	Net present value [€]	Water costs (irrigation costs and taxes) [€]	Agricultural gross Margin [€]
Environmental	Single impact Environmental Footprint score [mPts]	Duration of river flow below low-water regulating flow (LWRF)	Single impact Environmental Footprint score [mPts]
Social	Farmer working hours spent at producing renewable energy [h]	Farmer working hours spent at irrigating crops [h]	Farmer working hours spent for all technical operations other than irrigation [h]

c. Resource production and consumption indicators

The aim of the resource production and consumption indicators is to evaluate the desirability and viability of WEFN resource management scenarios through the estimation of energy and food production rates and water consumption rates

Energy production: Solar and wind integrated energy productions are computed with climate daily data produced by Météo France at SAFRAN grid scale. The SAFRAN grid scale is made from spatial polygons of 8km*8km surfaces (Tribouillois et al., 2022). Renewable energy production potentials of solar panels and wind turbines are estimated with equations 2 and 3 (Roth 2019). Energy produced by solar panels and wind turbines is obtained by integrating power equations 2 and 3. Equation 2 illustrates the linear function used to estimate solar energy production.

Equation 2: Linear function to estimate solar energy production

$$P_{PV}(t) = \begin{cases} 0 & \text{if } P_{PV} < 0 \\ \eta_{mod} \cdot \left(1 - C_{TP,max} \cdot \left(\left(T_{atm}(t) + \frac{NOCT-20}{800} \cdot G_{ir}(t) \right) - ref_{sol_{celltemp}} \right) \right) \cdot G_{ir}(t) \cdot S_{PV} & \text{if } 0 < P_{PV} < P_C \text{ [We]} \\ 255 & \text{if } P_{PV} > P_C \end{cases}$$

With:

- η_{mod} : Module efficiency
- $C_{TP,max}$: Temperature coefficient (%.°C-1)
- NOCT: Nominal Operating Cell Temperature (°C)
- $ref_{sol_{celltemp}}$: Reference cell temperature (°C)
- S_{PV} : Surface area of a PV cell (m²)
- P_C : PV peak power (W)
- $G_{ir}(t)$: Solar irradiance (W.m⁻²)
- $T_{atm}(t)$: Atmospheric temperature (°C) .

Equation 3 illustrates the linear function used to estimate wind turbine energy production.

Equation 3: Linear function to estimate wind turbine energy production

$$P_E(t) = \begin{cases} P_n \cdot \frac{V_{wind}(t) - V_{min}}{V_{nom} - V_{min}} & \text{if } V_{min} < V_{wind}(t) < V_{nom} \\ P_n & \text{if } V_{nom} < V_{wind}(t) < V_{max} \\ 0 & \text{if } 0 < V_{wind}(t) < V_{min} \end{cases}$$

With:

- P_n : Nominal power (W)
- V_{min} : Minimum wind speed (m.s⁻¹)
- V_{nom} : Nominal wind speed (m.s⁻¹)

- V_{max} : Maximum wind speed (m.s-1)
- $V_{wind}(t)$: Wind speed (m.s-1)

Note that the compliance of land characteristics and security distances with road, rail and air routes with national regulations on solar panels and wind turbines installation is verified in a previous step to only consider land that is eligible for wind and solar energy production.

Food production: Yields of harvested crops are estimated with Maelia’s Water-Food nexus simulations. Energy and proteins produced by agriculture are obtained with equations 4 and 5.

Equation 4: Agricultural energy yield derived from harvested crops

$$Energy [J] = Crop_{harvested}[kg]. Caloric\ content_{crop} \left[\frac{kcal}{kg} \right]. 4184 \left[\frac{J}{kcal} \right]$$

Equation 5: Proteins yield derived from harvested crops

$$Proteins [kg] = Crop_{harvested}[kg]. Proteins\ ratio\ of\ crop [.]$$

Water consumption: The aim of the water withdrawal indicator is to penalize irrigation water withdrawals gradually according to the water resource type from which water is retrieved from. Table 7 gives integers used for each water source type. Irrigation from surface rivers is penalized the hardest, followed by withdrawals from water tables and withdrawals from water reservoirs.

Table 7: Water integers used to compute the water withdrawal indicator

No irrigation	Surface water	Groundwater	Reservoir
0	3	2	1

The reason withdrawals from surface water canals are penalized the hardest is that numerous water conflicts exist among surface water users in water stressed territories. Withdrawals from water tables are the second hardest penalized because they deteriorate the environment and the ecosystems. Since surface water withdrawals are penalized the hardest, this indicator includes a social dimension. The water withdrawal indicator illustrates the crop management strategies’ degrees of water dependency and can evidence the potential synergies between renewable energy production and the limitation of contentious water withdrawals for irrigation.

d. Economic indicators

The aim of the economic indicators is to estimate and compare the economic desirability and viability of different WEFN resource management scenarios.

Energy economic evaluation: The net present value is computed to estimate the economic profitability of renewable energy production units. Solar panels’ and wind turbines’ net present values are obtained with equation 6.

Equation 6: Solar panels and wind turbines net present values (NPV)

$$NPV = -CAPEX + \sum_{n=1}^N \frac{(Gain(n) - OPEX(n) - A(n)) * (1 - \alpha) + A(n)}{(1 + r)^n} \text{ with } A(n) = \frac{CAPEX}{N}$$

N stands for the study period duration in years. CAPEX stands for capital expenditures and OPEX for operating expenses. α represents the tax rate and r the discount rate. The gain exemplifies the market electricity cost spared by the production of renewable energy during the study period.

Water and food economic evaluation: The agricultural gross margin is computed to estimate the economic profitability of crops. The agricultural gross margin includes water costs. Equation 7 details its calculation.

Equation 7: Agricultural gross margin

Agricultural gross margin [€] = *Income* [€] – *Costs* [€], where :

Income [€] = *Crop selling prices* [€/ha].*Yield* [ha]

Costs [€] = *Fertilizer* [€] + *Phytosanitary* [€] + *Fuel* [€] + *Water* [€], with :

Water [€] = *Irrigation costs* [€] + *Water taxes* [€]

e. Environmental indicators

Energy and food environmental evaluation : Environmental impact scores of energy production units and crops in agricultural land are calculated with the Environmental Footprint Method (European Commission, 2022) and characterize the impact a process has on 16 environmental categories such as climate change, acidification, eutrophication, ecotoxicity, land, water and resource use (Sala et al., 2020). Environmental impact scores are catalogued in well-known LCA databases: Ecoinvent (Wernet et al., 2016) for energy production units and Agribalyse (Ademe, 2024) for crops. The environmental impact score of energy production units under different WEF scenarios is evaluated in comparison with an initial reference situation. Figure 15 illustrates the approach.

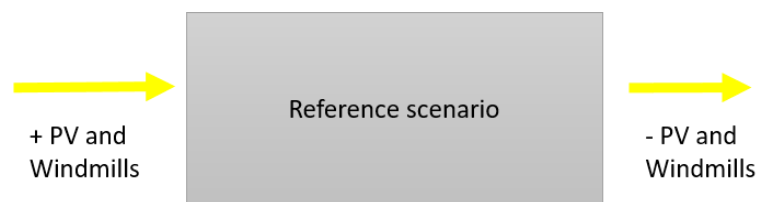


Figure 15: Illustration of the energy and food environmental evaluation approach

A scenario's energy environmental impact score is computed by doing the sum of the impacts of the renewable energy production units added to the reference scenario and subtracting the sum of the impacts of the renewable energy production units removed from the reference scenario. A scenario's crop environmental impact score is computed by doing the sum of the impacts of the crops produced under the distinct WEF scenarios considered. Meadows start absorbing carbon dioxide (and thus having a negative impact score) once they have been sowed for more than three years.

Water environmental evaluation : The duration of river flow below low-water regulating flow (LWRF) is computed to estimate the compliance of scenarios with water management national regulations that protect ecosystems and biodiversity. The low-water regulating flow is a threshold established by the European Parliament to ensure water sustainability (Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, 2000).

f. Social indicators

As a first indicator of social sustainability of WEFN scenarios, farmers' labour is estimated. The total number of hours farmers spend at irrigation and at other technical operations involved in crop management techniques are evaluated with Maelia. The total number of hours farmers spend producing renewable energy is considered null, since external experts ensure the installation and maintenance of renewable energy units.

g. Conclusion

The ten resource production and consumption, economic, environmental and social indicators listed below have been selected and designed to evaluate the sustainability of WEFN resource management scenarios.

1. Agricultural energy production - Energy agro [J]
2. Renewable integrated energy production [J]
3. Food proteins production – Proteins agro [kg]
4. Renewable energy net present value [€]
5. Gross agricultural margin – Gross margin agro [€]
6. Renewable energy environmental impact [mPts]
7. Agricultural environmental impact – EF agro [mPts]
8. Water withdrawal indicator – Water ind
9. Duration of river flow below low-water regulating flow – LWRF [days]
10. Number of farmer working hours – Farmer work [h]

Multi-criteria and multi-objective strategic decision-making methods developed for our multi-actor multi-level framework rely on these indicators to produce optimized land-use allocation scenarios that satisfy objectives of all actors of the same system.

V. Conclusions and perspectives

Chapter 2 has presented the generic tools and methodologies selected and developed to implement the multi-actor multi-level framework for WEFN systems presented in this manuscript. It has introduced the integrated spatialized multi-agent based modelling platform selected and parametrized for WEFN studies in agricultural land in France. The platform MAELIA, has been initially conceptualized to study integrated water-food systems in agricultural land at operational daily and field scales. An extension of the platform is planned to enable it to simulate complete operational WEFN systems. The extended version will enable simulating land-use allocation scenarios of renewable energy generation units in agricultural land under food and water constraints. This chapter has also shared the methodologies designed and implemented to evaluate the suitability of the land for solar panels and wind turbines. The strategic decision-making methods developed rely on these methodologies to design scenarios of renewable energy generation units allocations in agricultural land that comply with technical and regulatory constraints. Finally, this chapter has displayed and explained multi-criteria indicators selected to characterize economic, environmental and social dimensions of WEFN systems. These indicators enable the evaluation of the sustainability and synergy of scenarios simulated with the multi-agent based platform. They constitute input information for multi-criteria and multi-objective strategic decision-making methods developed for our multi-actor multi-level framework for WEFN systems.

The next chapter, chapter 3, details the multi-actor multi-level framework for WEFN systems introduced in this chapter and presents the first strategic decision-making approach designed.

VI. References

- Ademe, 2024. Agribalyse [WWW Document]. URL <https://agribalyse.ademe.fr/app> (accessed 3.5.23).
- ARVALIS, institut technique agricole grandes cultures et fourrages [WWW Document], 2024. URL <https://www.arvalis.fr/> (accessed 8.31.23).
- BD ALTI® | Géoservices [WWW Document], n.d. URL <https://geoservices.ign.fr/bdalti> (accessed 4.19.23).
- BD TOPO® | Géoservices [WWW Document], 2021. URL <https://geoservices.ign.fr/bdtopo> (accessed 8.30.23).

Christophe Leblanc, 2015. Evaluation environnementale du dossier présenté par la société BAALON ENERGIES pour l'exploitation d'un parc éolien sur le territoire de la commune de BAALON.

Dardonville, M., Bockstaller, C., Therond, O., 2021. Review of quantitative evaluations of the resilience, vulnerability, robustness and adaptive capacity of temperate agricultural systems. *J. Clean. Prod.* 286, 125456. <https://doi.org/10.1016/j.jclepro.2020.125456>

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy, 2000. , OJ L.

Elisabeth Borne, Emmanuelle Wargon, 2019. Eolien et urbanisme guide a destination des élus. European Commission, 2022. European Platform on LCA | EPLCA [WWW Document]. URL <https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html> (accessed 6.5.24).

GAMA Platform | GAMA Platform [WWW Document], 2024. URL <https://gama-platform.org/> (accessed 8.28.23).

Gerbaud, V., 2023. PSE prospective: Paradigm transition towards Complex Thought in a global world under pressure. *Comput. Chem. Eng.* 175, 108274. <https://doi.org/10.1016/j.compchemeng.2023.108274>

Giampietro, M., Aspinall, R., Bukkens, S., Cadillo, J., Diaz-Maurin, F., Flammini, A., Gomiero, T., Kovacic, Z., Madrid Lopez, C., Ramos-Martin, J., serrano-tovar, T., 2013. An Innovative Accounting Framework for the Food-Energy-Water Nexus: Application of the MuSIASEM approach to three case studies.

Les Systèmes de Coordonnées de Références — Documentation Briques de Géomatique 0.1 [WWW Document], n.d. URL <https://briques-de-geomatique.readthedocs.io/fr/latest/SCR-theorie-pratique.html> (accessed 9.1.23).

Martinez-Hernandez, E., Leach, M., Yang, A., 2017. Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. *Appl. Energy* 206, 1009–1021. <https://doi.org/10.1016/j.apenergy.2017.09.022>

Meuwissen, M.P.M., Feindt, P.H., Spiegel, A., Termeer, C.J.A.M., Mathijs, E., Mey, Y. de, Finger, R., Balmann, A., Wauters, E., Urquhart, J., Vigani, M., Zawalińska, K., Herrera, H., Nicholas-Davies, P., Hansson, H., Paas, W., Slijper, T., Coopmans, I., Vroege, W., Ciechomska, A., Accatino, F., Kopainsky, B., Poortvliet, P.M., Candel, J.J.L., Maye, D., Severini, S., Senni, S., Soriano, B., Lagerkvist, C.-J., Peneva, M., Gavrilescu, C., Reidsma, P., 2019. A framework to assess the resilience of farming systems. *Agric. Syst.* 176, 102656. <https://doi.org/10.1016/j.agsy.2019.102656>

Ministère de l'Écologie, du Développement durable, des Transports et du Logement, 2011. Installations photovoltaïques au sol - Guide de l'étude d'impact.

Occitanie, D., 2021. Porté à connaissance pour la mise en oeuvre de la planification territoriale des projets éoliens [WWW Document]. DREAL Occ. URL <https://www.occitanie.developpement-durable.gouv.fr/porte-a-connaissance-pour-la-mise-en-oeuvre-de-la-a25624.html> (accessed 4.19.23).

Raster Terrain Analysis Plugin [WWW Document], n.d. URL https://docs.qgis.org/2.18/en/docs/user_manual/plugins/plugins_raster_terrain.html (accessed 1.4.24).

- Roth, A., 2019. Développement de méthodologies génériques pour la conception optimale et durable des parcs hybrides d'énergies renouvelables (phdthesis). Institut National Polytechnique de Toulouse - INPT.
- Sala, S., Crenna, E., Secchi, M., Sanyé-Mengual, E., 2020. Environmental sustainability of European production and consumption assessed against planetary boundaries. *J. Environ. Manage.* 269, 110686. <https://doi.org/10.1016/j.jenvman.2020.110686>
- SWAT | Soil & Water Assessment Tool [WWW Document], 2024. URL <https://swat.tamu.edu/> (accessed 8.28.23).
- Therond, O., Sibertin-Blanc, C., Lardy, R., Gaudou, B., Balestrat, M., Hong, Y., Louail, T., Nguyen, V.B., Panzoli, D., Sanchez-Pérez, J.-M., Sauvage, S., Taillandier, P., Vavasseur, M., Mazzega, P., 2014. Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems. Presented at the 7th International Environmental Modelling and Software Society (iEMSs 2014), International Environmental Modelling and Software Society, p. 1.
- Tribouillois, H., Constantin, J., Murgue, C., Villerd, J., Therond, O., 2022. Integrated modeling of crop and water management at the watershed scale: Optimizing irrigation and modifying crop succession. *Eur. J. Agron.* 140, 126592. <https://doi.org/10.1016/j.eja.2022.126592>
- Vo, D.A., 2012. An operational architecture to handle multiple levels of representation in agent-based models (These de doctorat). Paris 6.
- Wallon, E. par D., 2021. Quelle est l'inclinaison optimale pour mes panneaux solaires ? URL <https://www.comwatt.com/blog/photovoltaique-autoconsommation/choisir/panneaux-solaires/inclinaison-optimale-panneaux-solaires/> (accessed 4.18.23).
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (Part I): Overview and methodology. *Int. J. Life Cycle Assess.* 21, 1–13. <https://doi.org/10.1007/s11367-016-1087-8>

Chapter 3: Generation of multi-actor water-energy-food nexus scenarios: Monte-Carlo simulations and multi-criteria decision-making

I. Introduction

Chapter 3 details the innovative generic water-energy-food nexus (WEFN) multi-actor multi-level framework developed during this PhD work and introduced in Chapter 2. The multi-actor multi-level framework advanced in this manuscript is modular and combines dynamic multi-agent operational simulations of water-energy-food systems with strategic decision-making methods. This chapter exposes the first approach developed to design strategic decision-making methods for the framework. This first approach is exploratory and stochastic. Three decision-making methods, one local (parcel level) and two regional (watershed level) have been designed with this approach. The reason for leading an exploratory and stochastic approach is that for land-use allocation problems, the multi-agent based platform introduced in chapter 2 produces daily data for every parcel of an entire territory. From the multi-agent based simulations of the reference agronomical scenario of the territory, other land-use allocation alternatives that include renewable energy generation units are defined and considered at parcel level. For watershed territories of around 15000 parcels, the number of possible combinations of parcel land-use allocations is infinite. Using classical multi-objective optimization techniques for these territories could result in long resolution times. This chapter also introduces the case study territory selected to illustrate the implementation of our multi-actor multi-level framework for land-use allocation problems. Given the absence of land allocation studies that simulate operational temporal and spatial multi-actor nexus systems to inform decision-making tools that allocate land-use types at small spatial scales, this manuscript has implemented the framework to solve a land-use allocation problem, but its generic formulation make it applicable to other nexus problems. This chapter is strongly inspired from an article published in *Computers and Chemical Engineering* (Saint-Bois et al., 2024). It shows how the framework finds optimal spatial allocations of renewable energy production units such as solar panels and wind turbines in agricultural landscapes under water constraints. Chapter 3 starts explaining the generic multi-actor multi-level framework and the first strategic decision-making approach designed for the framework. It then presents the case study chosen to illustrate the framework for land-use allocation problems. It continues sharing results and computational performances. It follows discussing the results and the chapter ends giving conclusions and presenting future perspectives.

II. Multi-level multi-actor WEFN framework and strategic decision-making based on Monte Carlo simulations and Multi Criteria Decision Making

a. Generic multi-level framework with strategic multi-criteria decision-making

Figure 1 illustrates the use of our generic multi-actor multi-level framework for WEFN systems with a strategic multi-criteria stochastic decision-making method as the strategic decision-making method used to implement the framework.

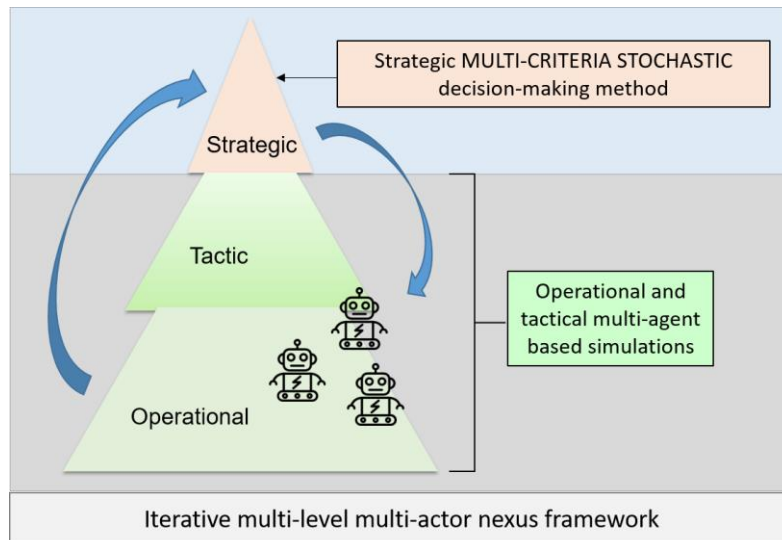


Figure 1: Multi-actor multi-level framework for WEFN systems with a strategic multi-criteria stochastic decision-making method

Figure 2 illustrates the methodological steps that must be followed to implement our framework with a strategic multi-criteria stochastic decision-making method. To implement our framework with the local and regional strategic multi-criteria stochastic decision-making methods developed, the first step identifies the case study region, the second one collects data and identifies possible parcel land-use alternatives and the third step establishes uniform strategic scenarios where each parcel is allocated the same land-use alternative or the reference agricultural land-use alternative if renewable energy related land-use alternatives are not possible for a parcel. The fourth step simulates the reference agricultural scenario at operational and tactical level and the fifth step uses outputs from these simulations and mathematical formulations of renewable energy production together with water and food hypotheses to characterize uniform regional scenarios that allocate land-use alternatives that combine agricultural crops and renewable energy generation units. The sixth step implements strategic decision-making methods to determine local and regional best land-use allocations. Uniform scenarios are defined in step 3 and characterized in step 5 with the aim of evaluating the nexus state of every parcel under every land-use alternative considered. Moreover, they serve as references to interpret scenarios resulting from strategic decision-making methods. This chapter introduces the stochastic and exploratory strategic multi-criteria decision-making approach developed to guarantee finding nexus management solutions at small spatial scales for large nexus systems. One local and two regional strategic multi-criteria decision-making methods are designed with this approach.

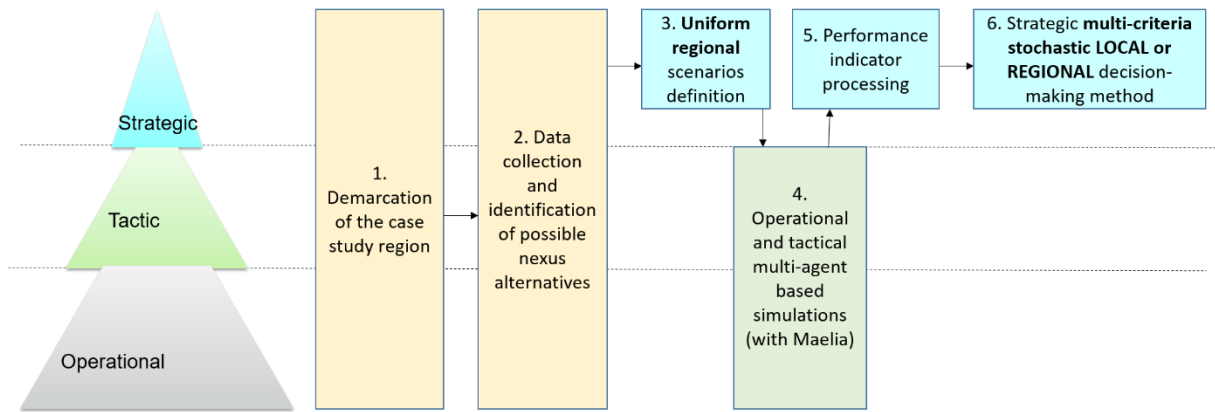


Figure 2: Generic methodological steps to lead a multi-level multi-actor approach for water-energy-food nexus land allocation problems in agricultural territories with strategic multi-criteria decision-making methods

Figure 3 details the methodological steps that must be followed to implement the framework with strategic multi-criteria decision-making methods to solve a water-energy-food nexus land allocation problem in the case study agricultural territory presented in this paper, which is composed of 15024 parcels.

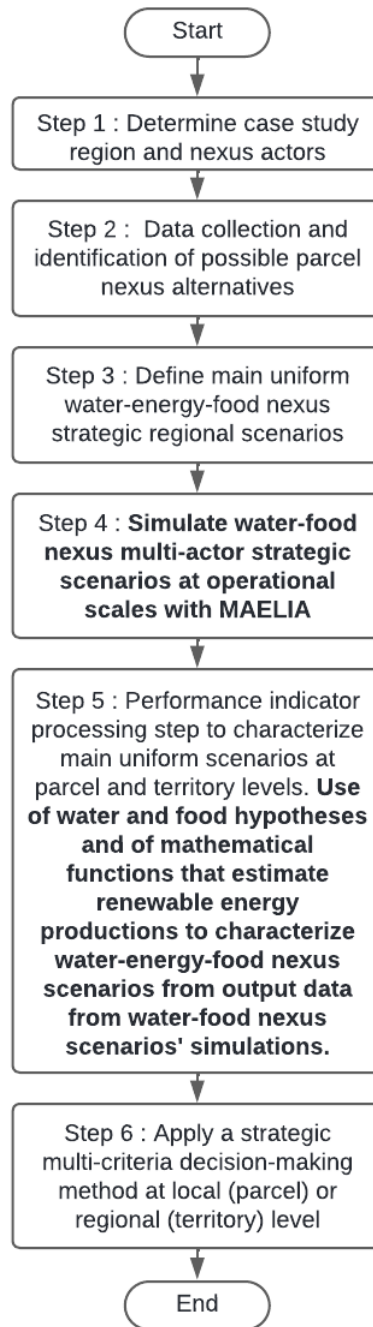


Figure 3: Steps to implement the multi-actor multi-level framework to solve a land-use allocation problem in large case study agricultural territories of about 15000 parcels

As shown in Figure 3, MAELIA (modeling of socio-agro-ecological systems for landscape integrated assessment), the multi-agent based platform developed by French researches (Therond et al., 2014) introduced in Chapter 2, is used to run multi-agent operational and tactical simulations of water-food scenarios of the case study region presented in this paper. MAELIA has been chosen to simulate operational scenarios of water-food nexus systems in agricultural land because it enables simulations of daily dynamics and interactions between farming and cropping systems, surface hydrology and ground water resources, dam releases and water use (Therond et al., 2014). Moreover, it has already been used to study water-food nexus systems in the case study region (Murgue et al., 2016). The Analytic Hierarchy Process

(AHP) method has been selected to design strategic multi-criteria decision-making methods because it is a hierarchical multi-criteria decision-making method that organizes multi-sector indicators in a set of criteria weighted with statistical or stakeholder data. Literature shows that it produces accurate results and that it is preferred over its generalized analytical network process version (Khan and Ali, 2020). Since the present version of MAELIA does not simulate complete water-energy-food nexus systems, simplifying water and food hypotheses and mathematical approximations of energy production units are used to characterize water-energy-food scenarios from output data of simulated water-food scenarios. The established simplifying hypotheses are introduced in section f. together with the performance indicator-processing step. Each step of the methodology shown in Figure 3 is detailed in specific paragraphs below.

b. Step 1 : Demarcation of the case study region

This first step of the methodology aims at identifying and demarcating territories where better management of water, land, agriculture and energy resources are needed, as well as at identifying stakeholders and major actors of these systems.

c. Step 2 : Data collection and identification of possible nexus alternatives

Step 2 assembles and analyzes data to identify possible configurations of nexus resources. If the framework is applied to allocate nexus alternatives to parcels, as it is the case for the present study, this step determines all possible parcel land-use allocations. Possible land-use allocations are identified for each parcel or piece of parcel, if parcels overlap more than one spatial meteorological polygon. Meteorological polygons are spatial geographical areas for which meteorological conditions are considered uniform. The parcel, or piece of parcel, constitutes the framework’s spatial decision unit. This is the case because the decision of installing energy production units such as windmills or solar panels in agricultural land depends on meteorological conditions and is administratively taken at parcel level. Parcels are identified with unique identifiers that can be found in national Land Parcel Identification Systems (LPIS). A parcel can overlap more than one meteorological polygon. Therefore, the generic methodology deals with spatial parcel entities characterized by tuples formed of a parcel and a meteorological polygon identifier. Spatial entities are illustrated in Figure 4.

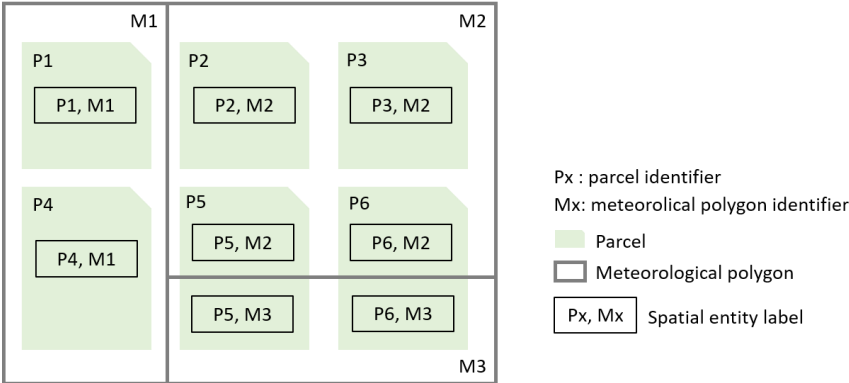


Figure 4: Parcels and meteorological polygons identifiers

In a water-energy-food nexus setting, agricultural parcels can be either entirely covered with agricultural crops, a mix of agricultural crops and energy production units, or entirely covered with energy production units. Considering windmills and solar panels as possible energy production units, four alternatives are identified for each parcel (Table 1): 100% Agro crop, Agrivoltaics (mix), 100% PV and 100% wind turbines.

Table 1: Four water-energy-food nexus parcel alternatives

100 % Agro	Agrivoltaics	100% PV	100 % Wind Turbines
The parcel is entirely covered with reference agricultural crops	<p><u>Suitable area</u> : 30% of the area is covered with solar panels and 70% with reference agricultural crops</p> <p><u>Non suitable area</u> : covered with reference agricultural crops</p>	<p><u>Suitable area</u> : 100% covered with solar panels</p> <p><u>Non suitable area</u> : covered with reference agricultural crops</p>	<p><u>Suitable area</u> : 100% covered with wind turbines</p> <p><u>Non suitable area</u> : covered with reference agricultural crops</p>

The first alternative considered for every parcel is the parcel entirely covered with crop rotations of the reference agricultural scenario. This alternative is referred to as the 100% Agro alternative. Other alternatives are only considered if parcels are partly or entirely suitable for the installation of renewable energy generation units. The methodology applied to evaluate the suitability of parcels to the installation of solar panels or wind turbines has been detailed in chapter 2. A parcel area is considered suitable to solar panels if its exposure is between 45° (north-east) and 315° (north-west) and if its slope is inferior to 60°. Practically, a raster of a digital elevation model is processed with QGIS’s raster terrain analysis plugin to derive values of parcels’ exposures and slopes. The eligibility to wind turbines is determined in two steps. The first step limits the land suitable to wind turbines to that included in areas declared suitable by governmental studies, if governmental studies exist for the case study region. The second step considers technical safety distances with power lines, airports, railways, residential areas, parks, nature reserves and vegetation formations and eliminates all parcel areas that do not respect safety distances. Practically, vector layers of infrastructures, residential areas and green spaces are processed to identify land that respects the required safety distances. If a parcel has some of its area suitable for solar panels, two more alternatives are considered for that parcel: an agrivoltaics alternative and a 100 % PV (photovoltaic) alternative. Under an agrivoltaics alternative 30% of the suitable parcel area is covered with solar panels and the other 70% are covered with agricultural crops. Parcel area that is not suitable for solar panels has agricultural crops. These percentages have been chosen according to farmers’ and governmental claims that 20% and 40% percent respectively of land coverage with solar panels does not deteriorate agricultural yields from more than 10% (“Décret agrivoltaïsme,” 2023). Under a 100% PV alternative parcel areas that are suitable for solar panels are entirely covered with solar panels and non-suitable areas are entirely covered with agricultural crops. Similarly, if some parcel area is suitable for wind turbines, a

100% Wind turbine alternative is considered in which parcel area suitable to wind turbines is fully covered with wind turbines and not suitable areas are covered with reference agricultural crops.

d. Step 3 : Scenarios definition

Step 3 defines uniform strategic regional scenarios from possible parcel alternatives identified in step 2. Step 3 starts by defining as many uniform regional scenarios as possible parcel alternatives. Under a uniform regional scenario all parcels are allocated the same alternative if their land is suitable for the given alternative and if not, they are allocated the reference agricultural alternative. The reason for defining uniform regional scenarios is that simulating nexus systems at operational scales is computationally expensive so step 4 of the methodological shown in Figure 3 only simulates uniform regional scenarios. Non-uniform regional scenarios' characterizations needed to implement strategic decision-making methods in step 6 of the methodology are derived from uniform regional scenarios' characterizations obtained in the performance indicator processing step (step 5) of the methodology. A baseline 100% agricultural scenario where each parcel is covered with the reference 100% agricultural alternative is always defined for agricultural territories. The agrivoltaics scenario corresponds to every suitable parcel being allocated an agrivoltaics alternative. The 100% PV scenario corresponds to every suitable parcel being allocated a 100% PV alternative. Similarly, a 100% wind turbine scenario can be defined if at least one parcel is suitable for wind turbines and if so it corresponds to every suitable parcel being allocated a 100% wind turbine alternative and the others an agricultural alternative. To estimate economic relevance of the scenarios, estimated energy payback time (EPBT) of solar panels and windmills in the study regions are computed and compared to benchmark values. EPBTs are computed by comparing energy production potentials of solar panels and wind turbines technologies considered in the case study region to energy life-cycle consumption values of similar solar panels and wind turbines technologies referenced in the Ecoinvent database (Frischknecht and Rebitzer, 2005). EPBTs are estimated with equation 1.

Equation 1 : EPBT

$$EPBT_{technology} [years] = \frac{Consumed\ energy\ through\ life\ cycle_{reference\ technology} [J] * Conversion\ factor}{Average\ yearly\ energy\ produced_{technology} [\frac{J}{years}]}$$

The conversion factor is computed with equation 2 and it is used to weight the energy consumed through the life cycle of the reference technology with the ratio of the peak powers of the two technologies compared.

Equation 2: Conversion factor for EBPT calculation

$$Conversion\ factor = \frac{Peak\ power_{technology} [KW]}{Peak\ power_{reference\ technology} [KW]}$$

Renewable energy production potentials of solar panels and wind turbines are estimated with equations 2 and 3 introduced in Chapter 2. Only economic relevant uniform regional scenarios are simulated in step 4.

e. Step 4 : Operational and tactical multi-agent based simulations

If a multi-agent based platform that simulates entire water-energy-food nexus is available, all uniform regional scenarios defined in step 3 are simulated at operational scales in step 4. Since for the given case study territory, no multi-agent based platform has been calibrated to simulate entire water-energy-food nexus systems, MAELIA, a multi-agent based platform that has been calibrated to simulate water-food nexus systems in the case study territory is used to simulate uniform water-food scenarios in step 4. Therefore, in step 4 of the methodology established for our case study territory, shown in Figure 3, the reference agricultural scenario is simulated operationally and tactically with MAELIA. Figure 5 illustrates Maelia's architecture and modules.

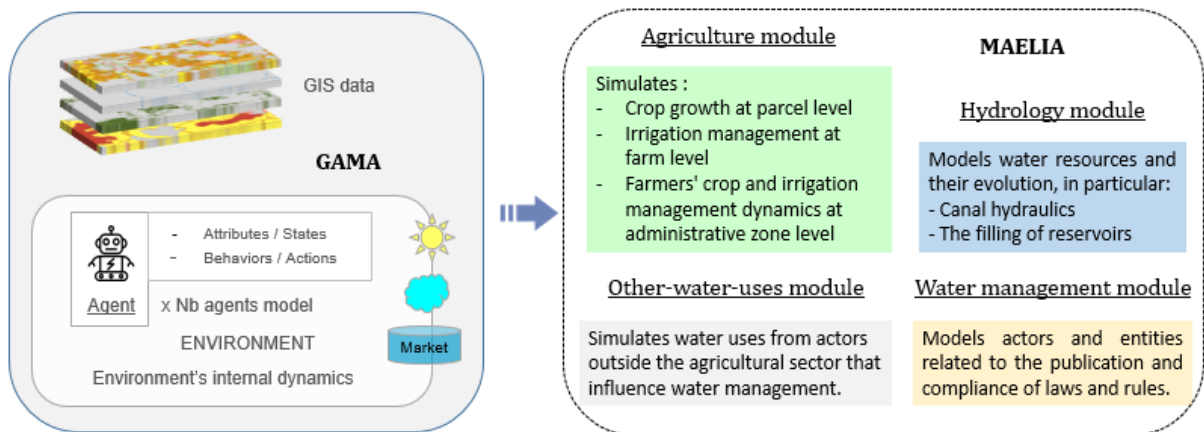


Figure 5: Maelia's architecture (GAMA based) and Maelia's modules (GAMA specification)

MAELIA's agriculture module simulates daily temporal dynamics of soil water and crop growth at parcel level and farmers' crop and irrigation management dynamics at parcel and farm level (for details see Tribouillois et al., 2018). A hydrology module simulates hydrology of water resources and the filling of farmer's small reservoirs. It is based on SWAT (Soil and Water Assessment Tool). A water management module simulates dam management and releases to sustain river flows and regulation of farmer irrigation. Finally, MAELIA also simulates water withdrawals for other users than farmers i.e. drinking water and industries. MAELIA provides a large set of daily outputs such as crop yields, farmer's gross margins and workload, river flows, dam releases and regulations (Therond et al., 2014). MAELIA has been described in details in Chapter 2.

f. Step 5: Performance indicator processing with water and food hypotheses

A performance indicator processing step is performed to characterize resource's states at parcel and territory level under the different uniform regional scenarios defined in step 3. Performance indicators selected for the case study region are introduced in the case study section below and have been described in Chapter 2. They characterize agricultural, hydrological, environmental and economical dimensions of the scenarios. To characterize uniform water-energy-food regional scenarios that have not been simulated with the multi-agent based platform in step 4 of the methodology, step 5 combines food and water outputs

from the simulation of the reference agricultural scenario with daily meteorological data to produce multi-sector water-energy-food nexus performance indicators. To compute water indicators of water-energy-food nexus scenarios, water outputs from the simulated agricultural scenario are used as a reference, and the following water hypotheses are established. It is assumed that if a solar panel or a wind turbine is placed on a parcel, the evapotranspiration (soil water evaporation and transpiration from plants) of the area covered with the renewable energy generation unit becomes null. It is also assumed that the amount of water that was evapotranspirated by the soil and plant of that parcel area under the reference agricultural scenario flows back to the main watercourse of the region under study. This is illustrated in Figure 6. Moreover, the total water released from reservoirs under the reference agricultural scenario is reduced by the total percentage of the territory that is covered with energy generation units times the percentage of parcels that withdraw water from reservoirs in the reference agricultural scenario. For example, to obtain the total water released from the water reservoir under the 100% PV scenario in Figure 6, the total water released from the water reservoir under the reference agricultural scenario must be multiplied by the yellow to green area ratio and by 0.02 (=ratio of parcels that retrieve water from reservoirs under the reference agricultural scenario in Figure 6).

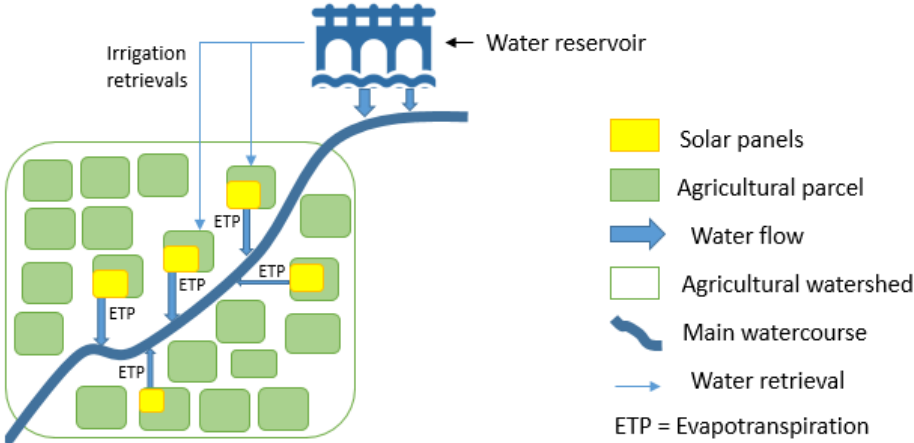


Figure 6: Water flows under a 100% PV scenario

Water reservoirs enable water resource management in water stressed areas. Flow deficits caused by high agricultural demands and water deficits are dealt with through water releases from reservoirs and withdrawal restrictions from regional authorities (Tribouillois et al., 2022). To compute food indicators of water-energy-food nexus scenarios, food outputs from the simulated agricultural scenario are used as a reference, and linear dependencies are assumed for every food related indicator. For instance, to compute a food production indicator of a parcel whose surface is covered up to 30% with solar panels under a water-energy-food scenario, it is assumed that the food production indicator of that parcel under the water-energy-food scenario is equal to the food production indicator of that parcel under the reference water-food scenario reduced by 30%. Topographical and daily meteorological data are processed to compute energy related indicators.

g. Step 6 : Strategic multi-criteria decision-making

Step 6 implements a strategic multi-criteria decision-making method to obtain land-use allocation scenarios that best satisfy multi-actor multi-criteria indicators. Three separate Analytic Hierarchy Process (AHP) based decision-making methods have been designed to derive strategic allocations of renewable power generation units in agricultural land under water constraints: one local (parcel level) decision-making method and two regional (territory level) decision-making methods. Analytic Hierarchy Process is a multi-criteria decision-making method that enables the evaluation of different alternatives' performances with respect to a certain goal. The evaluation is based on a set of performance indicators (previous step) normalized and aggregated into a set of criteria. The criteria are then weighted with a set of weights determined by either system experts, empirical data or both. The addition of the weighted normalized criteria results in a score for each alternative. The alternative with the highest score is considered the best solution for the given goal. The three decision-making methods are based on the previous evaluation of performance indicators of known uniform regional scenarios, where every parcel is allocated the same land-use alternative. A uniform regional scenario is defined for every known land-use alternative. The local decision-making makes one decision per parcel. Figure 7 illustrates the local decision-making method.

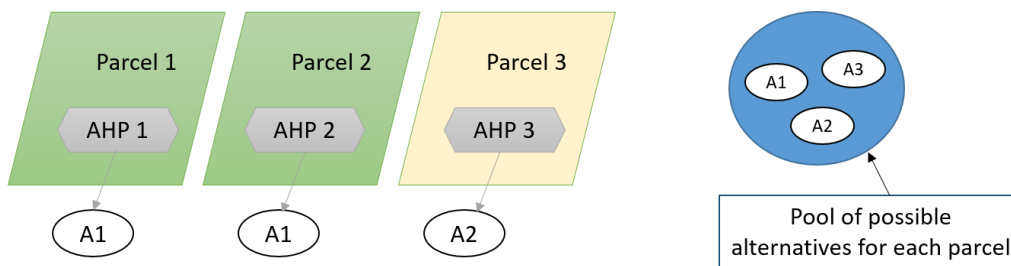


Figure 7: AHP based local decision-making method

As shown in Figure 7, the local decision-making method implements an AHP per parcel to select the best parcel land-use alternative. As opposed to the local decision-making method, regional decision-making methods base their decisions on regional performance indicators. Characterizing all possible combinations of parcel allocations is impossible because the number of combinations is infinite. The number of possible combinations equals the number of possible parcel allocations for each parcel entity**number of parcel entities, where the number of possible allocations for each parcel entity equals 3 and the number of parcel entities equals 16061 for the case study region, see case study section. Two regional decision-making methods based on Monte Carlo simulations have been designed to overcome this combinatorial challenge. Figure 8 illustrates the first one.

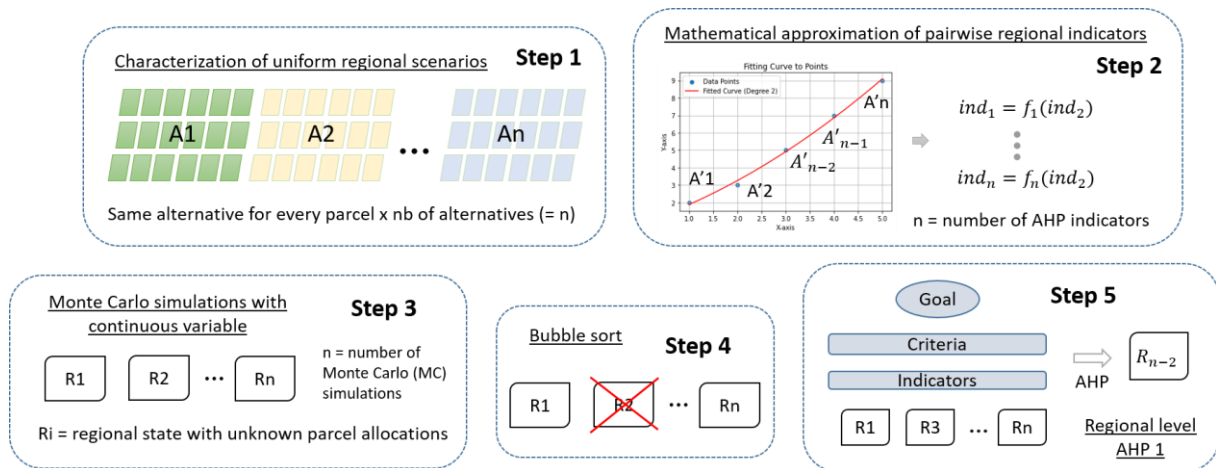


Figure 8: Regional decision-making method n^o1

The first step of the first regional decision-making method collects the characterizations of the uniform regional scenarios performed in step 5 of the methodology illustrated in Figure 3. The second step derives a set of optimized approximation curves (pseudo Pareto Fronts) for pairs of performance indicators. Optimized points (labeled A'_i in Figure 8) are obtained by adding or reducing 10% of error to performance indicator values of the uniform regional scenarios (labeled A_i in Figure 8) depending on whether the indicator in the y-axis is to be maximized or minimized respectively with respect to the indicator in the x-axis. A curve is fitted to the optimized points and mathematical approximations of the drawn curves are deduced for each pair of indicators. The third step runs Monte Carlo simulations using the approximated pseudo Pareto Fronts to derive points that correspond to optimized regional states of land-use allocations. The fourth step is a bubble sort that eliminates regional states produced in the previous step that are not Pareto-optimal. The fifth step runs an AHP to select the best Pareto regional state. The disadvantage of this method is that it does not allocate specific alternatives to parcels, since the solution obtained is a set of pseudo optimized regional performance indicator values. Parcel allocations can be derived in a supplementary step by searching for regional scenarios that have similar regional performance indicator values and for which parcel allocations are known. The second regional decision-making method, presented in Figure 9, overcomes this drawback.

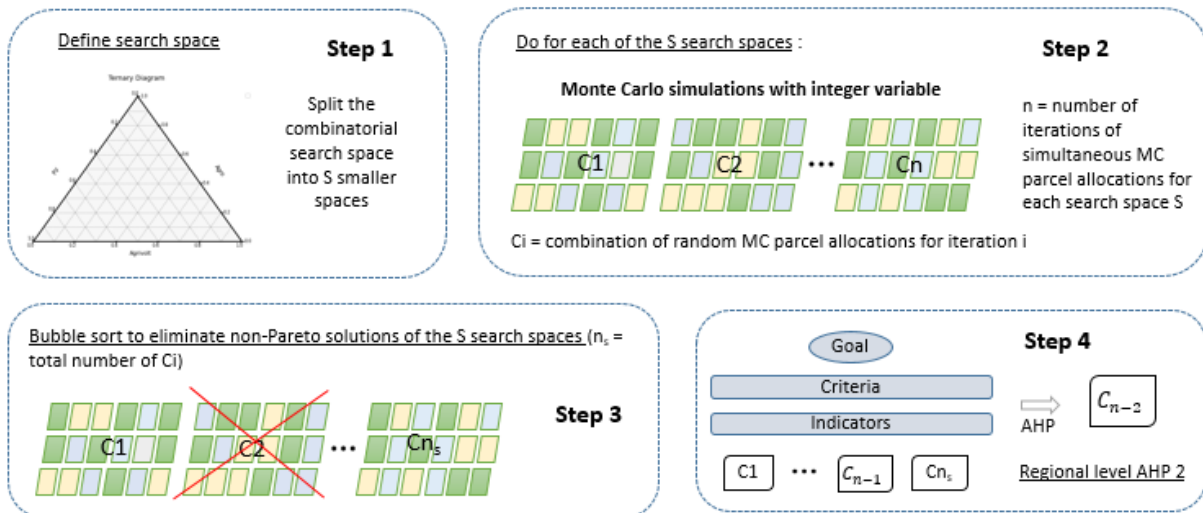


Figure 9: Regional decision-making method n°2

The second regional decision-making method starts by determining the combinatorial search space of possible combinations of land-use allocations to parcels and by splitting this search space into S smaller search spaces. The search space of possible combinations that appears in Figure 9 corresponds to a case study where three different alternatives can be allocated to each parcel and is therefore represented with a ternary diagram. The ternary diagram represents each alternative as a variable of the diagram with a scale that ranges from 0 to 1 to indicate the percentage of territory parcels covered with the corresponding alternative. The second step runs simultaneous Monte Carlo simulations that allocate random alternatives to parcels for each of the S search spaces. N Monte Carlo simulations are performed for each S search space. A Monte Carlo simulation of a given search space is constrained by the percentage of territory parcels that are allocated each of the possible alternatives, but the selection of parcels that are allocated each different alternative is random. The third step performs a bubble sort to eliminate non-Pareto solutions. The last step runs an AHP to determine the best regional Pareto scenario with respect to the multi-criteria performance indicators selected. The method splits the initial combinatorial search space into smaller search spaces and performs constrained Monte Carlo simulations for each smaller search space to ensure that all areas of the initial combinatorial search space are explored.

III. Case study

a. Study area

The framework's potential is illustrated through its application on an 840 km² agricultural watershed situated downstream the Aveyron river (South-West France, Fig. 10). It is situated in the French Adour-Garonne basin, which is the French basin with the highest annual structural water deficit, which is about 7hm³ on average (Tribouillois et al., 2022). Moreover, it is located in the Occitanie region, which is one of the sunniest regions in France. The total agricultural land is about 385 km² and is divided into 1150 farms and 15224 parcels. Irrigated agriculture developed in the region is responsible for 80% of the basin's total water

abstractions while the area represents 16% of the Aveyron's watershed total surface (Murgue, 2014). The two main rivers of the watershed are La Lère and L'Aveyron.

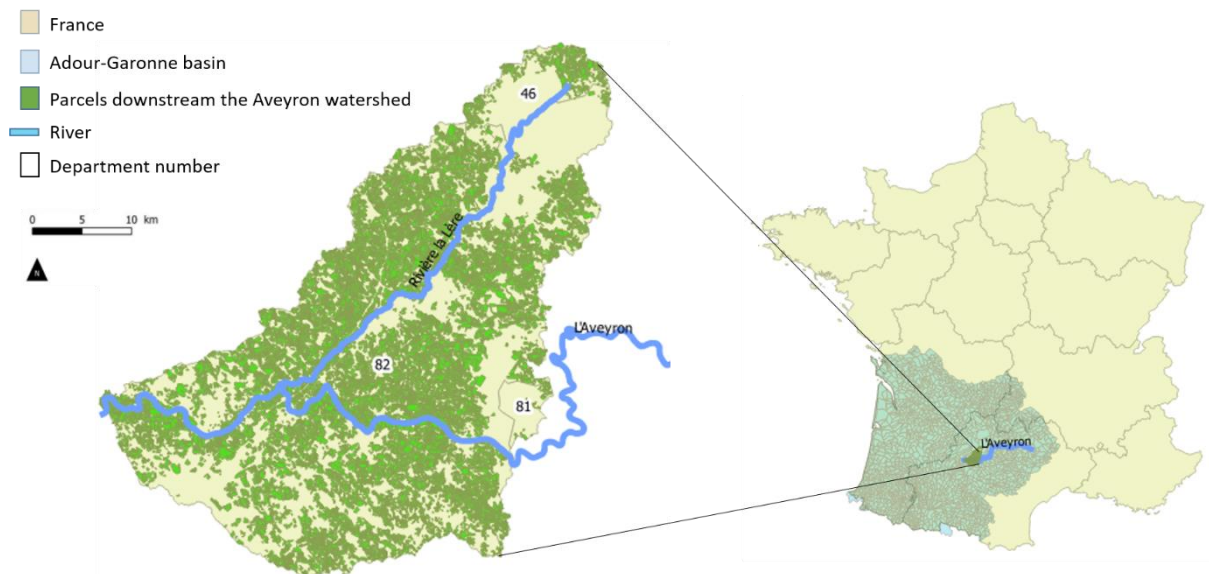


Figure 10: Case study region

b. Study period and input data

The case study period is a 20 year-period between 2006 and 2025. The reason for studying a 20 year-period is that it corresponds to the average lifespan of a solar panel. The reference agricultural scenario is simulated over a 10 year-period between 2006 and 2015 and results are duplicated to obtain data for the 2016 - 2025 period. The first reason for selecting 2006-2015 as the study period for the reference agricultural scenario is that previous studies have already worked on the characterization of cropping systems and crop management systems in the case study region over the 2006-2015 time period (Tribouillois et al., 2022). Moreover, water withdrawal volumes and river flow rates simulated with MAELIA have been validated over the study period 2007-2016 (Tribouillois et al., 2022). Similarly, MAELIA's simulations and predictions of crop yields, soil water content, evapotranspiration and drainage in fields cultivated with the main crop types present in the region over time periods earlier to 2016 have also been validated (Constantin et al., 2015; Tribouillois et al., 2018). Maize, durum wheat and sunflower seeds are the main crop types found in the area (Tribouillois et al., 2022). The 2006-2015 reference agricultural scenario has been duplicated to obtain data for the 2016-2025 period because crops and crop management systems are similar and water related data such as dam water releases is not easily available so a data-collecting step would have been necessary to work on a more recent period. Consequently, the 100% Agro benchmark scenario used in this study corresponds to the real parcels' agricultural situation for period 2006-2025, which is duplicated over the 2016-2025 period. Crop successions correspond to those recorded in the French Land Parcel Identification System and crop management and irrigation strategies to those obtained by previous work through dedicated farmer surveys (Murgue, 2014; Murgue et al., 2016). More information on the benchmark scenario can be found in (Murgue et al., 2016) and in (Tribouillois et al., 2022). All meteorological data is given at the scale of 8km *8Km surface polygons known as the SAFRAN grid (Tribouillois et al., 2022).

Energy related indicators are computed with simulated meteorological data corresponding to years 2006-2015 of the RCP 4.5 scenario (Moss et al., 2010). Tables 2 and 3 give the main parameters of the solar panel and wind turbine technologies used for this study, which correspond to technologies commercialized around 2015.

Table 2: Main parameters of the solar panel model used for the study

Model	η_{mod}	C_TP,max [%·°C-1]	NOCT [°C]	ref_sol_cell_temp [°C]	S_PV [m ²]	Pc [W]
PW2300 from PHOTOWATT	0.16	-0.43	45	25	1.46	255

Table 3: Main parameters of the wind turbine model used for the study

Model	Vmin [m.s-1]	Vnom [m.s-1]	Vmax [m.s-1]	Pn [W]
ALSTOM POWER 110	3	11.5	25	3000000

Table 4 presents the reference technologies used to compute EBPTs and gives their respective cumulative energy consumed during their entire life cycle.

Table 4: Reference technologies used to compute EPBTs

Technology	Peak power [KW]	Cumulative energy consumed [J]
Photovoltaic installation	3	2.6*10 ⁹
Wind turbine	2*10 ³	1.37*10 ¹³

No agricultural subsidies are considered for this study.

Table 5 and 6 show data used to compute solar net present values for the study period considered. Electricity costs are taken from (Jelloul and Douenne, 2016).

Table 5: Economic solar parameters

Capex [€/Wc]	Opex [%capex]	Discount rate	Tax rate	Study period duration [years]
1	0,024	0,06	0,3	20

Table 6: Electricity costs used to compute solar net present values for the study period considered

Cost [€/kwh]	Year
0,1079	2006
0,1079	2007
0,1094	2008
0,1096	2009
0,1089	2010
0,1168	2011
0,1225	2012
0,1329	2013
0,1401	2014
0,1437	2015

Appendix C gives crops technical itineraries' costs and appendix D gives crops' selling prices of all crops considered in the case study watershed. Crops' technical itineraries' costs include costs from fertilizers, phytosanitaries and fuels. Water costs are computed separately by aggregating irrigation costs (Appendix E) and water taxes (Appendix F). Crop's caloric and protein contents needed to compute agricultural production indicators are given in appendix G. Appendix H gives crops' environmental impact scores used to evaluate environmental footprints of crops. Appendix I gives environmental impact scores of renewable energy technologies considered for the case study region.

c. Case study strategic decision-making methods

The multi-criteria performance indicators introduced in Chapter 2 have been used to design the structure of the AHPs (Analytic Hierarchy Process) employed in the strategic multi-criteria decision-making methods developed. The performance indicators are categorised into four distinct criteria: (i) a food and energy production criterion that measures the quantities of energy and protein generated, (ii) an economic criterion that measures economic benefits and costs, (iii) an environment criterion that measures environmental footprints and water impacts and (iv) a social criterion that measures the number of hours worked by farmers. Equal weights are associated to the four criteria. Figure 11 illustrates the structure of the AHPs designed for the local and regional multi-criteria decision-making methods.

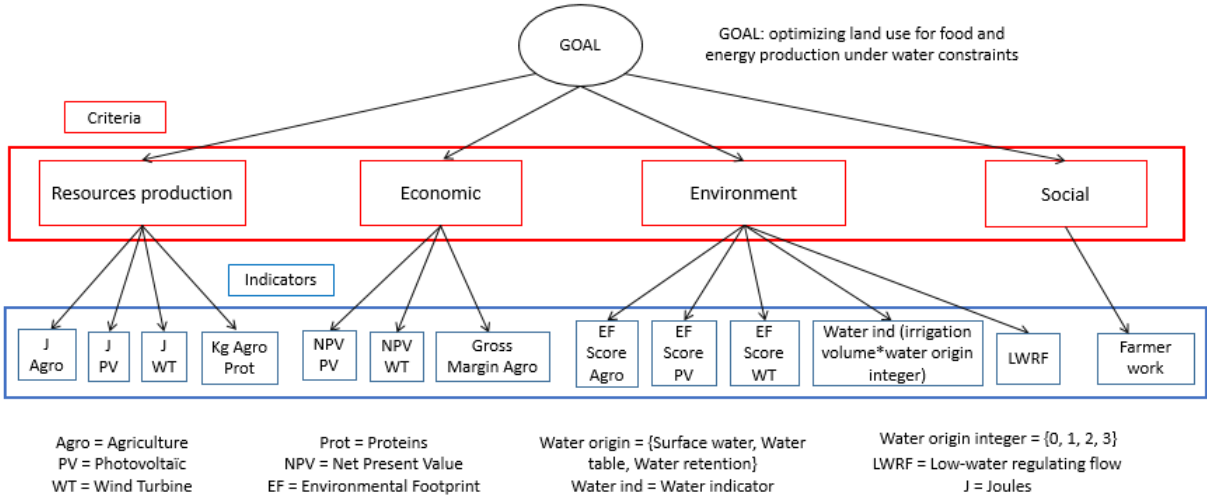


Figure 11: AHP structure

Indicators have been selected according to literature that evaluates sustainability, resilience and synergy of water-energy-food nexus systems. Indicators selected measure the three dimensions of sustainability: economical, environmental and social. More details on the selection of this indicators can be found in Chapter 2 and in (Saint-Bois et al., 2023).

Four indicators are used to measure resources production (i) energy (joules, J) from agriculture, (ii) solar panels and (iii) wind turbines and (iv) kilograms (Kg) of proteins from agriculture. Three indicators are used to measure economic performance. Solar panels and wind turbines' net present values and agricultural gross margin. Environmental performance is characterized with five indicators: (i) agricultural, (ii) solar and (iii) wind turbines

environmental impact scores, (iv) a water withdrawal impact indicator and (v) LWRF (low-water regulating flow). LWRF indicates the number of days during which the daily mean average flow rate of the Aveyron river is under the regulatory threshold i.e. 4.0 m³.s⁻¹ (Mazzega et al., 2014). This threshold has been established to preserve aquatic ecosystems (Tribouillois et al., 2022). Only one indicator is used to measure the social dimension: the total number of hours worked by farmers under the given scenarios.

Table 7 recapitulates performance indicators computed to feed input data for the strategic decision-making methods designed for our multi-level multi-actor framework.

Table 7: Summary of the performance indicators used as inputs of the strategic decision-making methods

Nb	Performance indicator - Notation	Significance
1	Agricultural energy production - Energy agro [J]	Total caloric energy derived from crops
2	Solar energy production - Energy PV [J]	Total electricity produced by solar panels
3	Wind energy production - Energy WT [J]	Total electricity produced by wind turbines
4	Food proteins production – Proteins agro [kg]	Total proteins derived from crops
5	Solar net present value – NPV PV [€]	Total solar net present value
6	Wind net present value – NPV WT[€]	Total wind turbine net present value
7	Gross agricultural margin – Gross margin agro [€]	Total gross agricultural margin
8	Agricultural environmental impact – EF agro [mPts]	Life cycle environmental footprint score Ecoinvent (“ecoinvent v3.0 - ecoinvent,” 2020)
9	Solar environmental impact – EF PV [mPts]	Life cycle environmental footprint score taken from Ecoinvent (“ecoinvent v3.0 - ecoinvent,” 2020)
10	Wind environmental impact – WT PV [mPts]	Life cycle environmental footprint score taken from Ecoinvent (“ecoinvent v3.0 - ecoinvent,” 2020)
11	Water withdrawal indicator – Water ind	Total volume of water withdrawn for irrigation weighted by an integer associated to each water source (see Table 7 of chapter 2)
12	Duration of river flow below low-water regulating flow – LWRF [days]	Total period duration of river flow below low-water regulating flow (LWRF)
13	Number of farmer working hours – Farmer work [h]	Total hours farmers spend at work to carry out crops’ technical itineraries

IV. Results

a. Identification of parcel alternatives and scenarios definition

The suitability study of the case study's parcels to solar panels has shown that every parcel has some of its area suitable for solar panels and that 99.59 % of the total initial agricultural surface is suitable for solar panels. The mean solar EPBT (energy payback time) is equal to 0.12 years, which represents a little bit more than one and a half month (Figure 12).

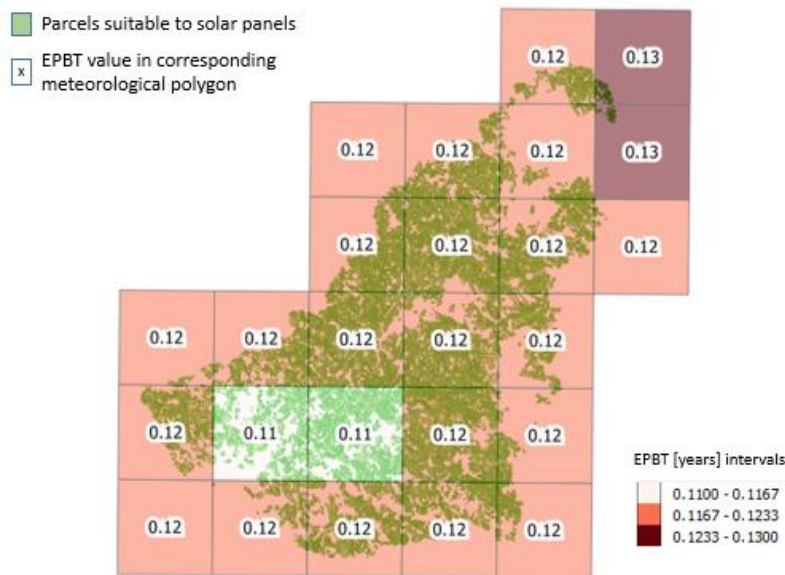


Figure 12: Land suitable to solar panels and EPBT values per meteorological polygon

The suitability study of parcels to wind turbines has shown that only 0.85 % of the total agricultural surface is suitable for wind turbines. EPBTs of the area that is suitable to wind turbines range from 3 to 7 years (Figure 13).

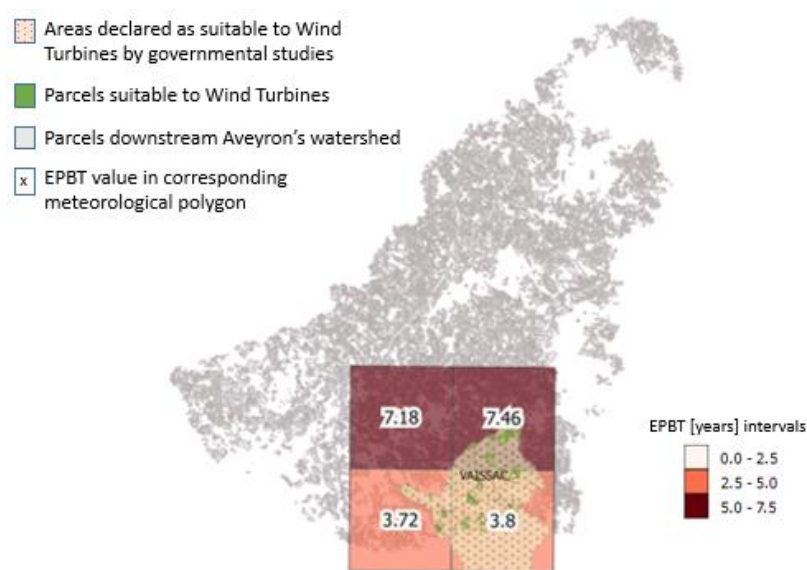


Figure 13: Land suitable to wind turbines and EPBT values per meteorological polygon

Considering that the surface suitable to wind turbines is very small and that the EPBTs are big compared to regular accepted EPBT that are rarely longer than 1 year (Yildiz et al., 2021), wind turbines have not been considered as possible energy production units in the case study region.

Accordingly, three uniform regional water-energy-food nexus scenarios have been considered: 100% Agriculture, Agrivoltaics and 100% PV (Table 8).

Table 8: Three uniform regional water-energy-food nexus scenarios evaluated over the 2006-2025 period

Scenario name	Scenario description
100 % Agriculture	Every parcel is covered with agriculture (100% Agro alternative in every parcel)
100% PV	Parcel areas that are suitable to solar panels are covered with PVs and other areas are covered with reference agricultural crops. (100% PV alternative in every parcel)
Agrivoltaics	30 % of the parcel areas that are suitable to solar panels are covered with PVs and other areas are covered with reference agricultural crops. (Agrivoltaics alternative in every parcel)

100% agricultural and 100% PV scenarios are the two extreme regional scenarios that can be allocated to the territory in terms of agricultural surface covered with solar panels.

b. Uniform scenarios' regional indicators

Table 9 shows performance indicators obtained for the three uniform regional water-energy-food nexus scenarios considered. Figure 14 identifies tradeoffs through a spider graph with performance indicators of the three uniform regional scenarios.

Table 9: Performance indicators of the three uniform regional water-energy-food nexus

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer work [h]
Agrivolt	2.78E+16	7.74E+17	1.94E+08	7.58E+09	-2.99E+08	6.85E+09	7.46E+07	3.20E+08	355	5.00E+05
100_ AGRO	3.97E+16	0.00E+00	2.77E+08	0.00E+00	-4.26E+08	0.00E+00	1.06E+08	4.55E+08	932	7.13E+05
100_ PV	2.09E+14	2.58E+18	1.29E+06	2.53E+10	-2.33E+06	2.28E+10	4.35E+05	4.03E+06	0.00	3.35E+03

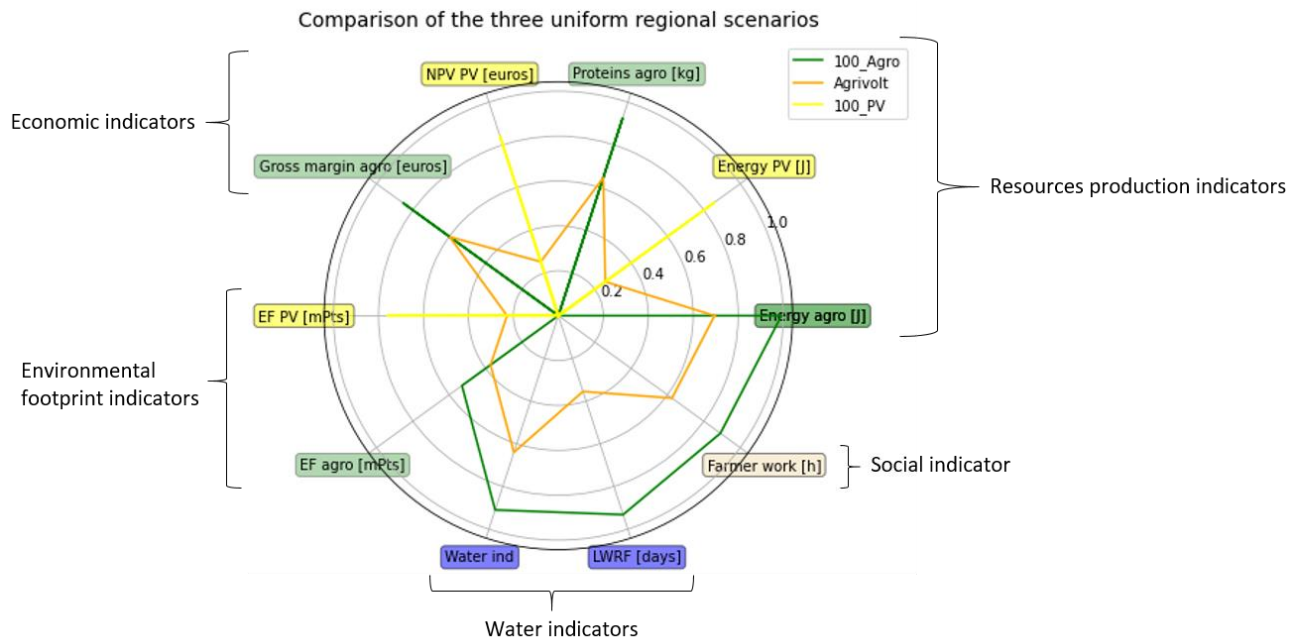


Figure 14: Spider graph with performance indicators of the three uniform regional water-energy-food scenarios considered

As expected, the agrivoltaics scenario is a compromise scenario between the 100% Agro and the 100% scenario since agrivoltaics' performance indicators are always in between values of 100% Agro and 100% PV indicators. Under a 100% PV scenario, absolute values of agricultural indicators (Energy agro [J], Proteins agro [kg], EF agro [mPts], Gross margin agro [euros], Farmer work [h]) and the water indicator are very small compared to values of the 100% Agro scenario and accordingly seem null in Figure 14. LWRF [days] is actually null under a 100% PV scenario (Table 9), meaning that the Aveyron's river water flow would never go under the governmental threshold under such scenario. Solar indicators (Energy PV [J], EF PV [mPts], NPV PV [euros]) of the 100% Agro scenario are null since no solar panel is installed in the territory under a 100% Agro scenario. Agricultural margins are always negative. This is because no agricultural subsidies are considered for the simulations and in France most agricultural activities become profitable for farms only with governmental subsidies (Commission des comptes de l'agriculture and de la Nation, 2022). Table 9 shows that the installation of solar panels has a positive impact on the water system since LWRF is null under a 100% PV scenario and under an Agrivoltaics scenario its value is less than half that of the reference 100% Agro scenario. Moreover, the water indicator decreases as the number of solar panels installed increases. Table 9 shows that solar panels have a higher environmental footprint than agriculture and a 100% PV scenario produces less proteins than a 100% agricultural scenario.

Table 9 and Figure 14 have illustrated tradeoffs and show that a competition exists between solar panels and crops in agricultural land. There is a consequent need to identify compromise solutions through the application of multi-criteria decision-making methods.

c. Results of the multi-criteria strategic decision-making methods

The local decision-making method has allocated a 100% PV land-use alternative on every parcel. This means that at parcel level, the 100% PV land-use alternative performs better than the Agrivoltaics or the 100% Agro alternative with respect to the 10 indicators selected. Figure 15 illustrates the resulting 100% PV regional scenario. Agricultural land (shown in green in Figure 15) is present under a 100% PV regional scenario since not all parcel land is suitable for PVs.

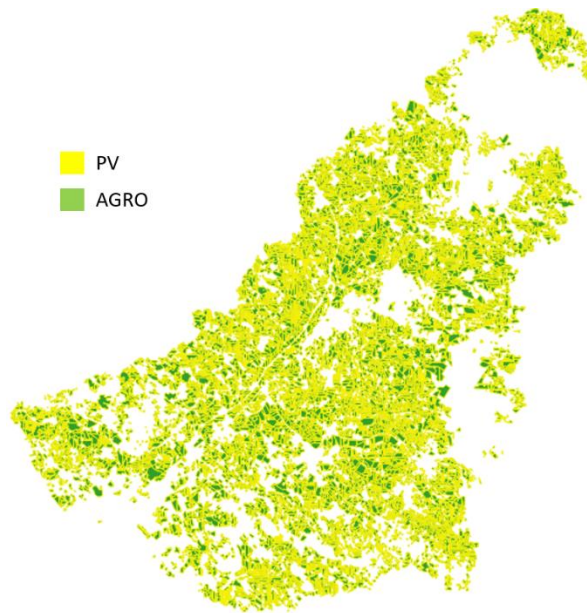


Figure 15: Spatial representation of a 100% PV regional scenario

16061 parcel entities are shown in Figure 15. They derive from the combination of 15224 parcels and 25 meteorological polygons present in the case study region.

The first step of the first regional decision-making method collects or creates characterizations of uniform regional scenarios. For the case study region, uniform regional scenarios described in Table 8 (100% Agro, 100% PV scenario and Agrivoltaics) and three variations of the standard Agrivoltaics scenario have been used. Under the standard Agrivoltaics scenario 30% of a parcel's land that is suitable for solar panels is covered with solar panels. The three variations of the standard Agrivoltaics scenarios account respectively with 25%, 50% and 75% percent of a parcel's land that is suitable for solar panels covered with PVs. Optimized scenarios are derived by improving performance indicator values of the four Agrivoltaics scenarios with 10% error margins to obtain approximated pseudo Pareto Fronts. Appendix A shows points in the pseudo Pareto Front in blue and the red point characterizes the solution scenario obtained with the first regional decision-making method, named the AHP regional 1 scenario. Figure 16 shows a spider graph that compares territory indicators of the AHP regional 1 scenario to territory indicators of the three uniform regional scenarios shown in Table 8. Table 10 shows performance indicator values of the AHP regional 1 scenario and Table 11 summarizes total absolute deviations between territory indicators of the AHP regional 1 scenario and indicators of the three uniform regional scenarios shown in Table 8.

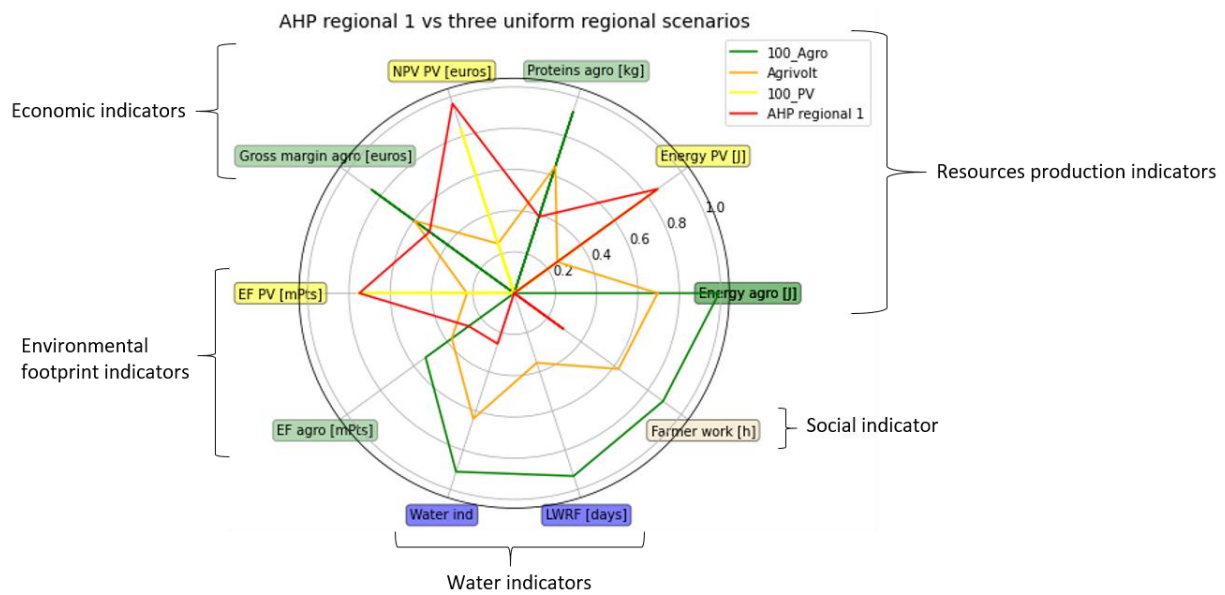


Figure 16: Spider graph of the territory indicators resulting from the first regional decision-making method and the three uniform regional scenarios

Figure 16 illustrates that the AHP regional 1 scenario resembles the 100% PV scenario in terms of solar and food energy productions (Energy PV [J], Energy agro [J]), solar net present value (NPV PV [euros]), solar environmental footprint (EF PV [mPts]), and in terms of water indicators (water indicator and LWRF). But the AHP regional 1 scenario is most similar to an Agrivoltaics scenario in terms of proteins production, gross agricultural margin and agricultural environmental footprint (EF agro [mPts]). Figure 16 illustrates the net present value of the AHP regional 1 scenario is higher than that of the 100% PV uniform regional scenario. This result is incoherent since no scenario can result in a higher solar net present value than the 100% PV uniform regional scenario.

Table 10: Performance indicators of the AHP regional 1 scenario

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer work [h]
AHP regional 1	0.00E+00	2.58E+18	1.17E+08	2.90E+10	-2.53E+08	2.25E+10	5.44E+07	1.29E+08	0	2.36E+05

Table 10: Absolute deviations between performance indicators of the AHP regional 1 scenario and indicators of the three uniform regional scenarios

	Total absolute deviation
100_AGRO	2.62E+18
100_PV	7.29E+14
Agrivolt	1.83E+18

When all indicators are combined, table 11 shows that the AHP regional 1 scenario is most similar to the uniform 100% PV regional scenario.

Figure 17 displays the initial combinatorial search space of possible combinations of land use allocations to parcels explored with the second regional decision-making method for the case study region. A ternary diagram is used to visualize the search space since for the case study region studied in this paper three possible alternatives exist for each parcel: 100% Agriculture, 100% PV and Agrivoltaics, labeled Agro, PV and Agrivolt respectively in Figure 17.

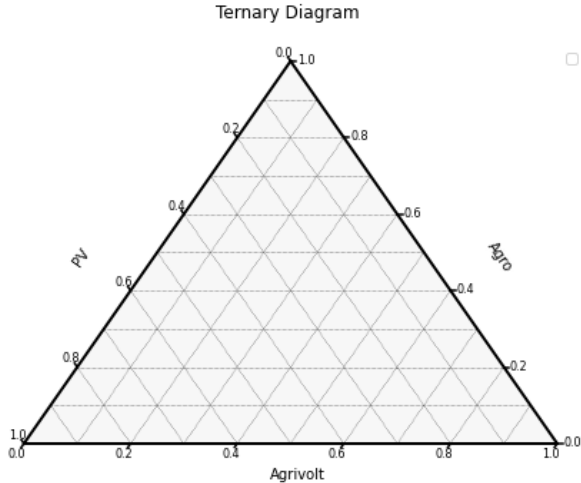


Figure 17: Search space of possible combinations of land use allocations to parcels explored with the second regional decision-making method

The initial combinatorial search space has been split into 15 search spaces shown in Appendix B. These search spaces are characterized by given percentages of territory parcels covered with 100% Agro, Agrivoltaics and 100% PV alternatives. 100 Monte Carlo simulations have been run for each search space, resulting in 1500 regional Pareto scenarios. The AHP shown in Figure 12 applied to these 1500 regional Pareto scenarios has selected a 100% PV regional uniform scenario as the best scenario out of the 1500 regional Pareto scenarios.

Table 14 summarizes results obtained from the implementation of the three distinct strategic decision-making methods and compare them with scenarios presented in Table 8.

Table 11: Take away results of the implementation of the three decision-making methods and comments

<u>Method</u>	<u>Closest uniform scenario wrt AHP indicators</u>	<u>Alternatives allocations to parcels</u>	<u>Water indicators (Water ind and LWRF)</u>	<u>Comments</u>
Local decision-making method	100 % PV	All parcels are assigned a 100% PV alternative	Equal to those of the 100% PV scenario	Agricultural and agrivoltaics alternatives are not assigned.
First regional decision-making method	100 % PV	Unknown	LWRF is null. Water indicator is bigger than that of the 100% PV scenario.	Null agricultural energy production and solar net present value of the AHP regional 1 scenario higher than

				that of the 100% PV uniform scenario are not coherent.
Second regional decision-making method	100 % PV	All parcels are assigned a 100% PV alternative	Equal to those of the 100% PV scenario	Agricultural and agrivoltaics alternatives are not assigned.

Results from the different decision-making methods applied to the case study region show that agricultural alternatives are not considered optimal with respect to the multi-criteria indicators selected. Significant negative agricultural gross margins and high water indicator values of the 100% agro and agrivoltaics alternatives can explain these results.

d. Computational performances

Table 15 illustrates the computational performances of the multi-actor approaches developed. The simulation of ten years of the reference 100% agricultural scenario takes a bit more than a day (31 h 22 min) to be completed with a standalone computer that accounts with 48 CPU cores and a Linux operating system (Intel® Xeon® Silver 4214R, 16,5 Mo, 2,40 GHz). The other steps are all implemented with Python and QGIS with a windows laptop (Intel(R) Core(TM) i5-10210U CPU @ 1.60GHz 2.11 GHz, 64 bits operating system). The performance indicator processing steps that need to be performed to apply any of the three decision-making methods designed take a bit less than 50 minutes. The local and the first regional AHP based decision-making method last 6 minutes and the second regional method lasts 5 hours and 30 minutes.

Table 12: Computation times and materials used for each implementation step of the decision-making tools

Step N°	Step	Computation time	Material
1	MAELIA simulation of 100% Agro scenario (10 years)	31 h 22 min	Standalone computer
2	100% Agro scenario - Performance indicator processing	24 min	Windows laptop
	100% PV scenario - Performance indicator processing	17 min	
	Agrivoltaics scenario - Performance indicator processing	< 1 min	
3.a.	Local decision-making method	6 min	Windows laptop
3.b.	First regional decision-making method	6 min	
3.c.	Second regional decision-making method	5 h 30 min	

The local and first regional decision-making methods take almost 33 hours to run and the second regional decision-making method takes almost 38 hours to run.

V. Discussion

a. Main results of the strategic decision-making methods

Both the local and second regional multi-criteria decision-making methods have produced scenarios equal to the 100% PV uniform regional scenario described in Table 8. The result from the local decision-making method indicates that at local (parcel entity) level, the 100% PV alternative scores better for all parcel entities with respect to the multi-criteria indicators selected than 100% Agro and Agrivoltaics alternatives. The result from the second regional

decision-making method indicates that from all 1500 Pareto scenarios compared, characterized by diverse coverage percentages of PV, Agrivoltaïcs and Agro parcels, regional indicators are at their best when all parcel entities are allocated a 100% PV alternative. Regional indicators are obtained by aggregating parcel indicators. Significant negative agricultural gross margins can explain 100% Agro and Agrivoltaïcs alternatives scoring less good than 100% PV alternatives. Moreover, selected water and social indicators penalize 100% Agro and Agrivoltaïcs. If the land uses were compared on resources production or environmental footprint levels, agricultural alternatives would score better. However, their bad economic, water and social performances result in local and regional decision-making methods selecting 100% PV land uses over 100% Agro and Agrivoltaïcs land uses.

The scenario resulting from the first regional multi-criteria decision-making method is most similar to the 100% PV uniform scenario described in Table 8 than to 100% Agro and Agrivoltaïcs uniform regional scenarios. Null agricultural energy production and a net present value higher than that of the 100% PV uniform regional scenario are incoherent. These results challenge the first regional decision-making method. They question the accuracy of the mathematical approximations used to predict indicator values in step 3 of the first regional decision-making method (see Figure 8). Therefore, the first regional decision-making method should not be used to predict exact indicator values, but to identify the best regional solution from those known.

These results challenge the realism of simulating a scenario with no agricultural subsidies. All three strategic multi-criteria decision-making methods have shown that at parcel and regional level covering all the land that is suitable for solar panels with solar panels is the best scenario with respect to the multi-criteria indicators selected. It would be interesting to see how accounting for governmental agricultural subsidies impacts the results. (Avraamidou et al., 2018) insist on the impact governmental subsidies have on the optimal solution found. Indeed, with wind and agricultural subsidies, the optimal solution found for a fictional piece of land is a mix between crops production and wind energy generation. Without agricultural subsidies, the share of renewable energy generation increases. Results from (Avraamidou et al., 2018) go along with those obtained in this study. That is to say, governmental subsidies play an important role for agricultural alternatives to be considered optimal with respect to multi-sectoral criteria. Results also question the social indicator used, since it only accounts for farmers' work and overlooks work from energy technicians and engineers. A 100% PV scenario is not viable in the case study region since a traditionally agricultural watershed would stop producing crops and switch from being a food exporting territory to a food importing territory. Additionally, farmers would lose their jobs since their number of working hours would drastically decline.

b. Advantages, drawbacks and perspectives

Table 16 compares the three multi-actor multi-criteria decision-making methods developed by summarizing specific aims, utilities, advantages and drawbacks.

Table 13: Aims, utilities, advantages and drawbacks of the multi-criteria decision-making methods developed

Method	Aim	Utility	Advantage	Drawbacks
Local decision-making method	Guide decisions made at parcel level : The decision of installing energy production units in agricultural land is done at parcel level so the method could be very helpful	Can serve as a tool to facilitate exchanges between energy actors and farmers at parcel level	The method selects the best alternative for each parcel with respect to a set of multi-criteria and multi-actor indicators	Does not take into account decisions made at neighboring parcels
First regional decision-making method	Guide regional decision-makers : Help them with investments and water regulation decisions	Can serve as a tool to facilitate exchanges between regional governors and farmers	Identifies best regional scenario from those known	The method does not allocate alternatives to parcels. It does not accurately predict indicator values.
Second regional decision-making method			Allocates alternatives to parcels	Limited computationally when the number of possible parcel alternatives increases.

The local decision-making method is recommended for energy actors or farmers looking to evaluate the impact energy production units have on parcels. The method can facilitate communication among them by providing information derived from multi-criteria and multi-actor evaluations and simulations. The two regional decision-making methods can guide regional decision-makers' decisions on investments or water regulation policies and facilitate exchanges with farmers. The first regional decision-making method identifies the best regional scenario from those known and the second one allocates alternatives to parcels.

VI. Conclusions and perspectives

This chapter has portrayed the first multi-actor multi-level framework that combines operational and tactical multi-agent based simulations with strategic decision-making methods to find resource management solutions for water-energy-food nexus systems. MAELIA is used as the multi-agent based tool to simulate operational and tactical dynamics of the agricultural and hydrological systems in the case study region. MAELIA simulates dynamic operational simulations of biophysical and hydrological systems and their interactions with humans. The platform relies on daily meteorological data and topographical information to produce data that is transformed into multi-sector strategic performance indicators. This chapter has introduced an exploratory and stochastic approach developed to design strategic decision-making methods for the framework. One local (parcel level) and two regional (watershed level) decision-making methods have been designed with this approach. The decision-making methods implement the Analytic Hierarchy Process (AHP) method for multi-criteria decision-making. The local decision-making method performs an AHP in every parcel

of the territory. The first regional decision-making method derives approximated Pareto Fronts from known uniform regional land-use scenarios for ten performance indicators and uses these pseudo Pareto Fronts to run Monte Carlo simulations that produce 1000 stochastic nexus states. It then applies an AHP to select the best nexus state and compares it to known uniform regional land-use scenarios. The second regional decision-making method defines a search space of possible combinations of parcel land-use allocations and splits this search space into 15 smaller search spaces. Each search space is characterized by given percentages of parcels being allocated each land-use alternative considered. A hundred Monte Carlo simulations are run to create different scenarios for each search space. A general AHP is then applied to select the best scenario from the entire search space. This chapter has also described the French case study territory selected to illustrate the multi-actor multi-level framework for land-use allocation problems. The case study territory is situated downstream the Aveyron river located south of France and accounts with around 800 km² and 15000 parcels. Results for the case study territory have shown that at parcel and regional level covering all the land that is suitable for solar panels with solar panels is the best option with respect to the multi-criteria performance indicators selected. This solution is nonetheless not viable for a traditional agricultural watershed. Solutions obtained can be explained by the fact that no agricultural subsidies have been considered and in France agricultural is almost never profitable without governmental subsidies. A perspective is thus to implement the approach considering governmental subsidies. Moreover, it would make sense to consider labour from energy actors as an additional performance indicator for the multi-criteria decision-making technique. This would strengthen the multi-actor aspect of the approach and solutions are expected to change and to shift towards scenarios that include higher numbers of parcels being allocated agricultural or agrivoltaics land-use alternatives.

The next chapter presents the second approach developed to perform strategic decision-making for the multi-actor multi-level framework established for WEFN systems. It conceptualizes a multi-objective optimization problem conceived for land-use allocation problems with many objectives. Mixed Integer Linear Programming and Goal Programming are combined to model the multi-objective land-use allocation problem. The multi-objective optimization approach is tested on the same case study territory as the one presented in this chapter. IBM's ILOG CPLEX optimization studio is used to model and solve the problem.

VII. References

Avraamidou, S., Beykal, B., Pistikopoulos, I.P.E., Pistikopoulos, E.N., 2018. A hierarchical Food-Energy-Water Nexus (FEW-N) decision-making approach for Land Use Optimization, in: Eden, M.R., Ierapetritou, M.G., Towler, G.P. (Eds.), *Computer Aided Chemical Engineering, 13 International Symposium on Process Systems Engineering (PSE 2018)*. Elsevier, pp. 1885–1890. <https://doi.org/10.1016/B978-0-444-64241-7.50309-8>

Commission des comptes de l'agriculture, de la Nation, 2022. LES DOSSIERS.

Constantin, J., Willaume, M., Murgue, C., Lacroix, B., Therond, O., 2015. The soil-crop models STICS and AqYield predict yield and soil water content for irrigated crops equally well

- with limited data. *Agric. For. Meteorol.* 206, 55–68.
<https://doi.org/10.1016/j.agrformet.2015.02.011>
- Décret agrivoltaïsme : le gouvernement tranche sur un taux de couverture maximal de 40% [WWW Document], 2023. URL <https://www.pleinchamp.com/actualite/decret-agrivoltaïsme-le-gouvernement-tranche-sur-un-taux-de-couverture-maximal-de-40> (accessed 3.8.24).
- Frischknecht, R., Rebitzer, G., 2005. The ecoinvent database system: a comprehensive web-based LCA database. *J. Clean. Prod., Life Cycle Assessment* 13, 1337–1343.
<https://doi.org/10.1016/j.jclepro.2005.05.002>
- Jelloul, M.B., Douenne, T., 2016. La TICPE dans le module de fiscalité indirecte de TAXIPP.
- Khan, A.U., Ali, Y., 2020. ANALYTICAL HIERARCHY PROCESS (AHP) AND ANALYTIC NETWORK PROCESS METHODS AND THEIR APPLICATIONS: A TWENTY YEAR REVIEW FROM 2000-2019. *Int. J. Anal. Hierarchy Process* 12. <https://doi.org/10.13033/ijahp.v12i3.822>
- Mazzega, P., Therond, O., Debril, T., March, H., Sibertin-Blanc, C., Lardy, R., Sant’Ana, D., 2014. Critical Multi-level Governance Issues of Integrated Modelling: An Example of Low-Water Management in the Adour-Garonne Basin (France). *J. Hydrol.* 519, 2515.
<https://doi.org/10.1016/j.jhydrol.2014.09.043>
- Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. *Nature* 463, 747–756. <https://doi.org/10.1038/nature08823>
- Murgue, C., 2014. Quelles distributions spatiales des systèmes de culture pour limiter l’occurrence des crises de gestion quantitative de l’eau ? Une démarche de conception évaluation sur le territoire irrigué de l’Aveyron aval (phd).
- Murgue, C., Therond, O., Leenhardt, D., 2016. Hybridizing local and generic information to model cropping system spatial distribution in an agricultural landscape. *Land Use Policy* 54, 339–354. <https://doi.org/10.1016/j.landusepol.2016.02.020>
- Saint-Bois, A., Boix, M., Montastruc, L., Therond, O., 2023. Simulating Renewable Energy Production Scenarios Under Water and Food Constraints. *Chem. Eng. Trans.* 105, 457–462. <https://doi.org/10.3303/CET23105077>
- Saint-Bois, A., Boix, M., Therond, O., Montastruc, L., Villerd, J., Touche, I., 2024. Multi-actor approach to manage the water-energy-food nexus at territory scale. *Comput. Chem. Eng.* 108773. <https://doi.org/10.1016/j.compchemeng.2024.108773>
- Therond, O., Sibertin-Blanc, C., Lardy, R., Gaudou, B., Balestrat, M., Hong, Y., Louail, T., Nguyen, V.B., Panzoli, D., Sanchez-Pérez, J.-M., Sauvage, S., Taillandier, P., Vavasseur, M., Mazzega, P., 2014. Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems. Presented at the 7th International Environmental Modelling and Software Society (iEMSs 2014), International Environmental Modelling and Software Society, p. 1.
- Tribouillois, H., Constantin, J., Murgue, C., Villerd, J., Therond, O., 2022. Integrated modeling of crop and water management at the watershed scale: Optimizing irrigation and modifying crop succession. *Eur. J. Agron.* 140, 126592.
<https://doi.org/10.1016/j.eja.2022.126592>
- Tribouillois, H., Constantin, J., Willaume, M., Brut, A., Ceschia, E., Tallec, T., Beaudoin, N., Therond, O., 2018. Predicting water balance of wheat and crop rotations with a

simple model: AqYield. Agric. For. Meteorol. 262, 412–422.

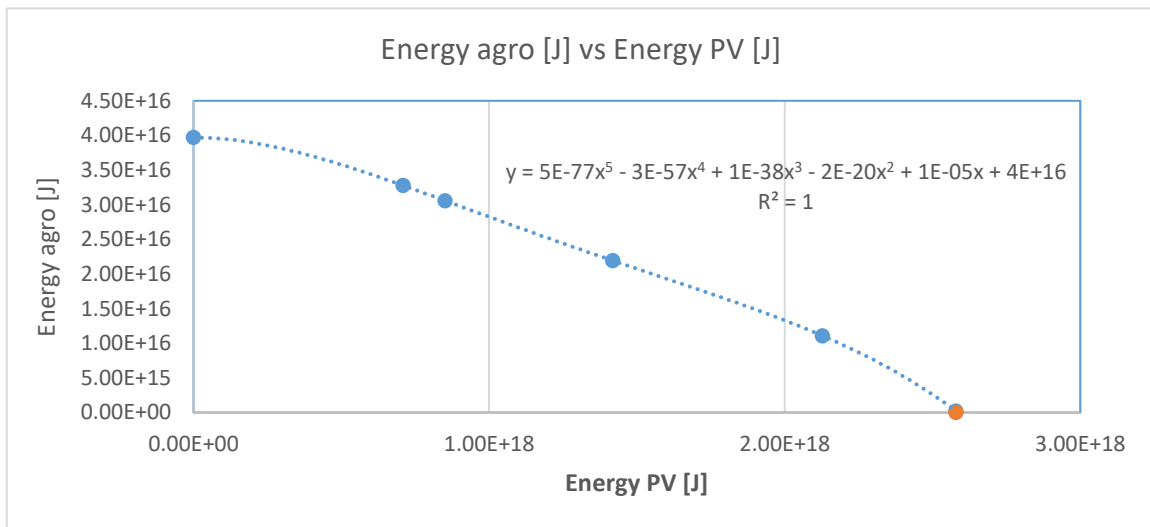
<https://doi.org/10.1016/j.agrformet.2018.07.026>

Yildiz, N., Hemida, H., Baniotopoulos, C., 2021. Life Cycle Assessment of a Barge-Type Floating Wind Turbine and Comparison with Other Types of Wind Turbines. Energies 14, 5656. <https://doi.org/10.3390/en14185656>

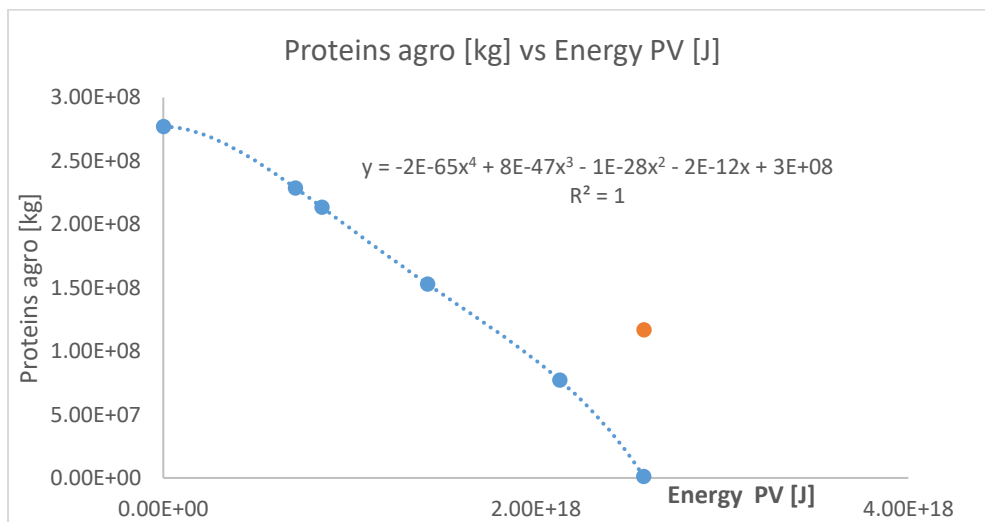
VIII. Appendices

- a. Appendix A: Pseudo Pareto fronts and mathematical approximations used to implement the first regional decision-making method

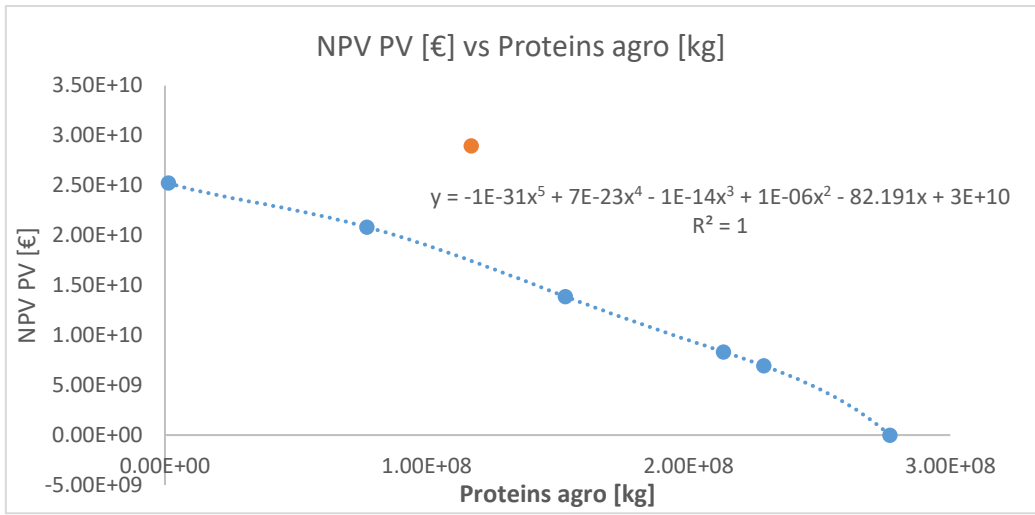
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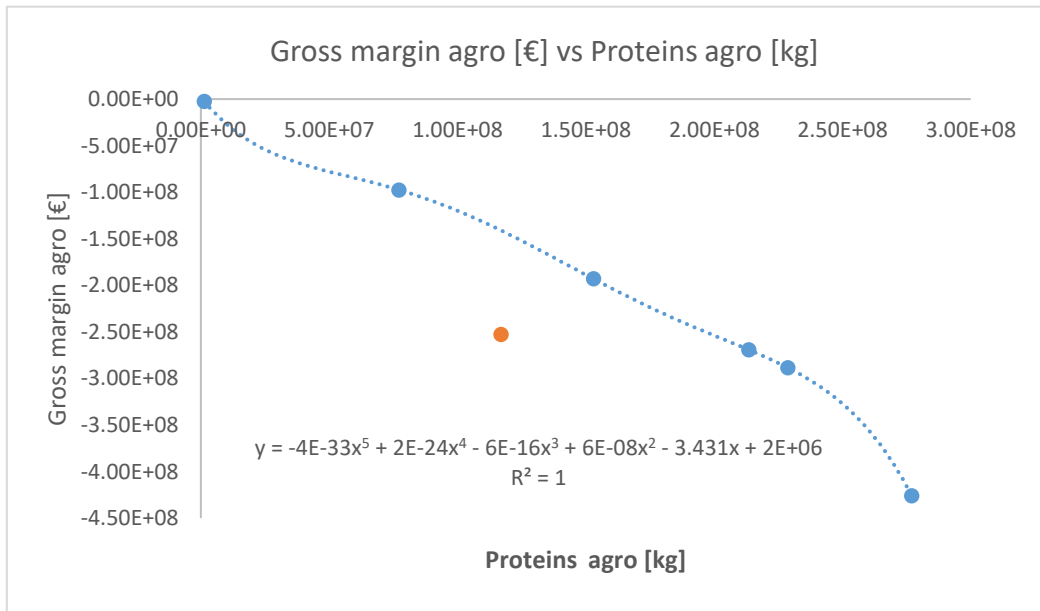
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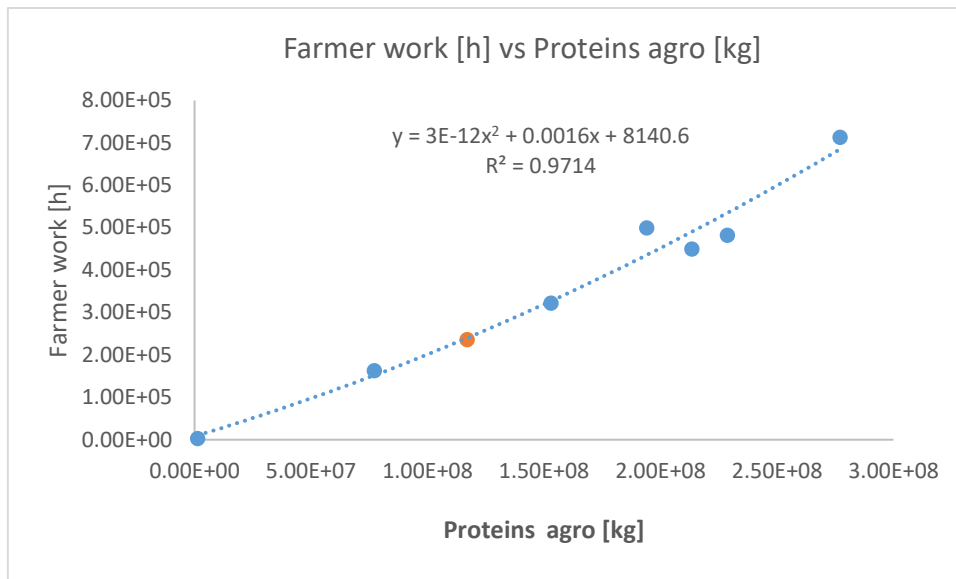
3. Pseudo Pareto front 3 :



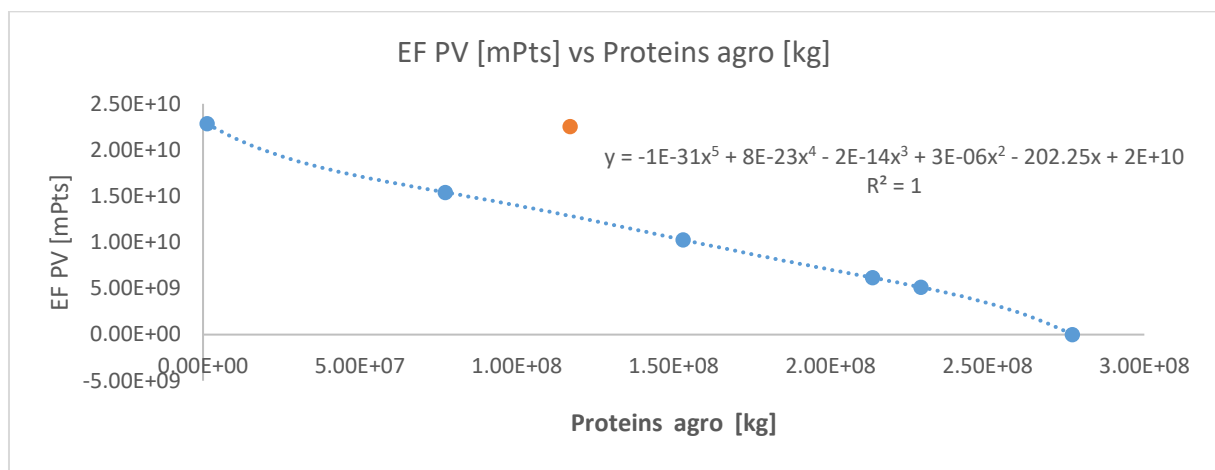
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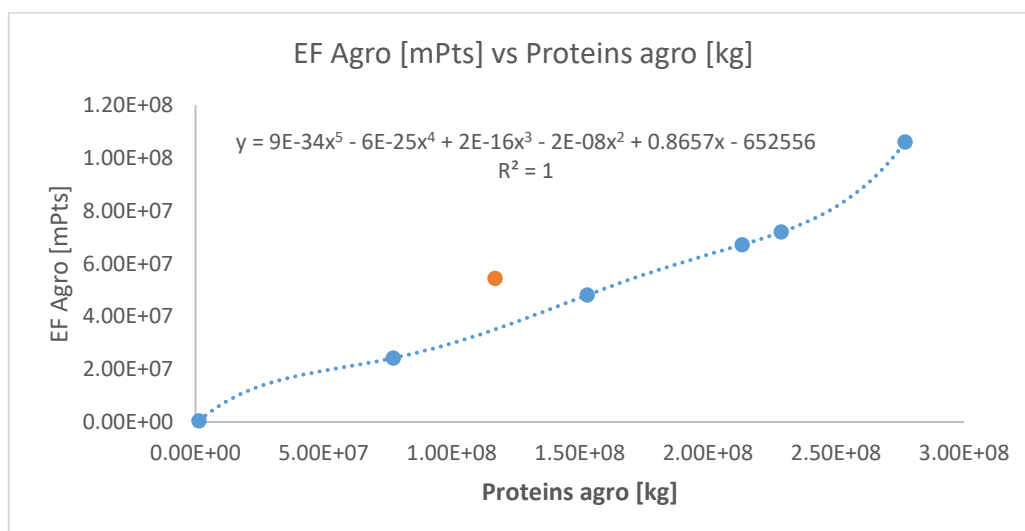
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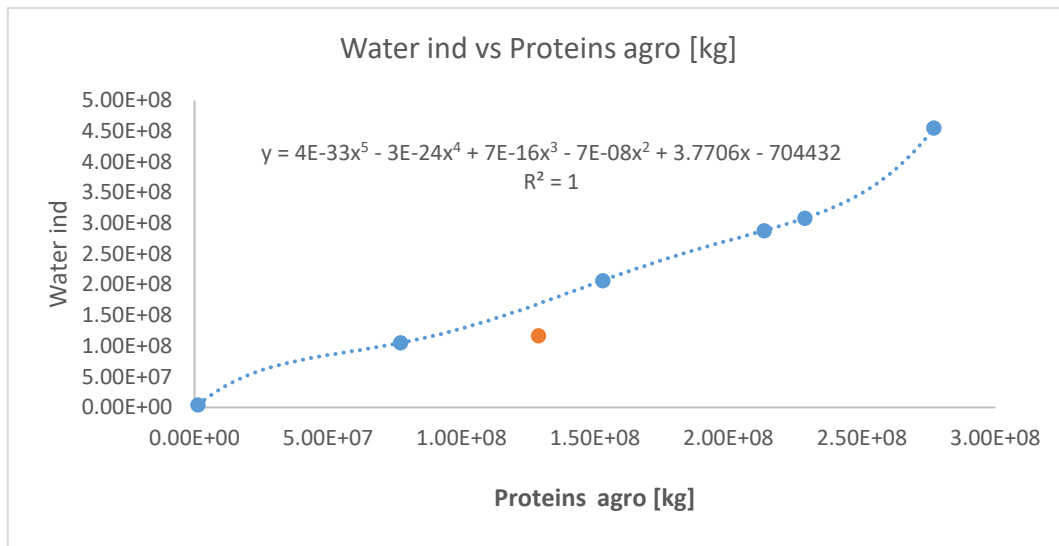
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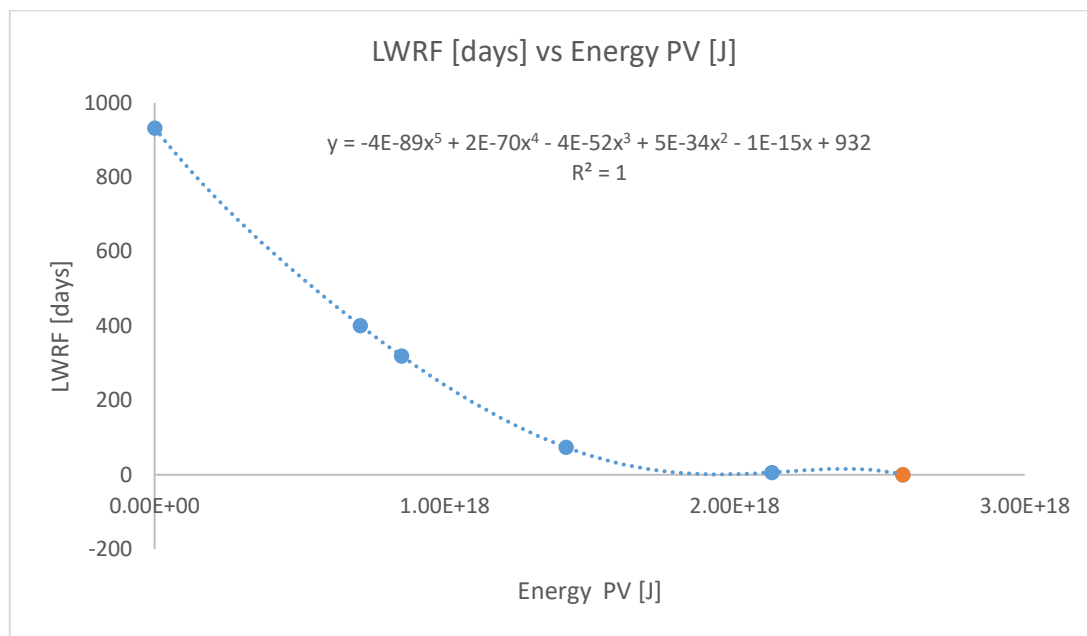
7. Pseudo Pareto front 7 :



8. Pseudo Pareto front 8 :

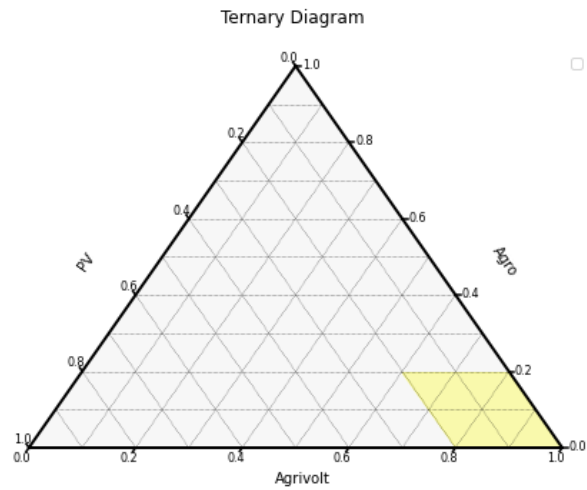


9. Pseudo Pareto front 9 :

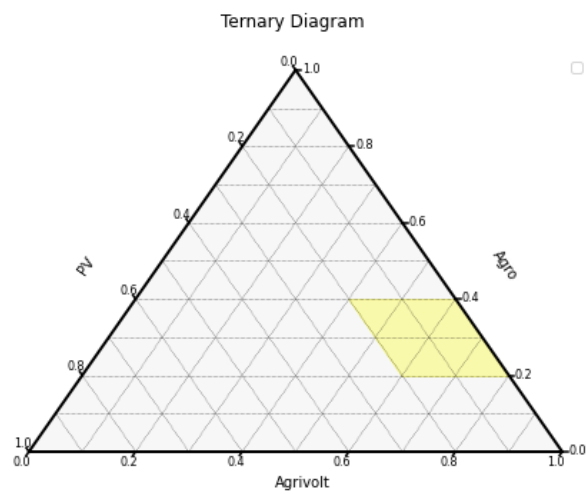


b. Appendix B: Search spaces explored with the second regional decision-making method

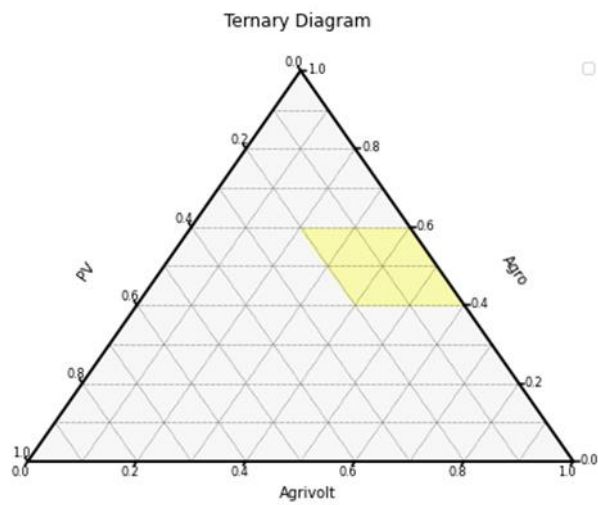
1. 0.0 ≤ PV ≤ 0.20 and 0.0 ≤ Agro ≤ 0.20



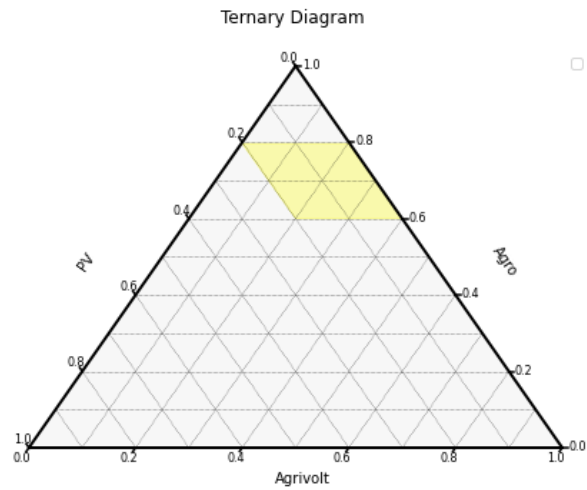
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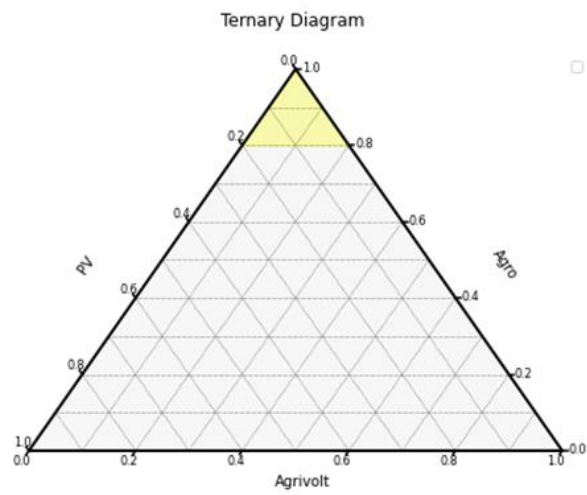
3. $0.0 \leq PV \leq 0.20$ et $0.40 \leq Agro \leq 0.60$



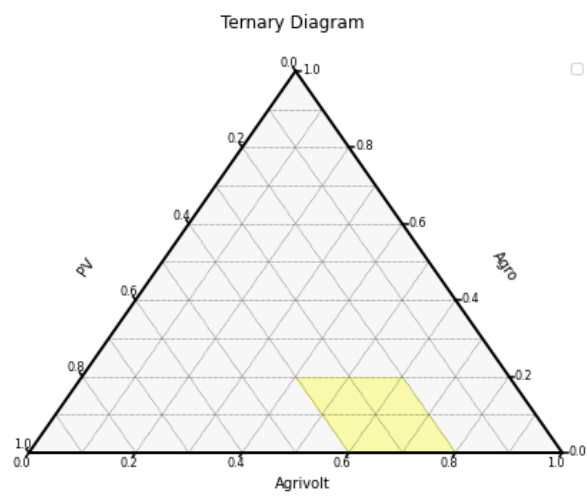
4. $0.0 \leq PV \leq 0.20$ et $0.60 \leq Agro \leq 0.80$



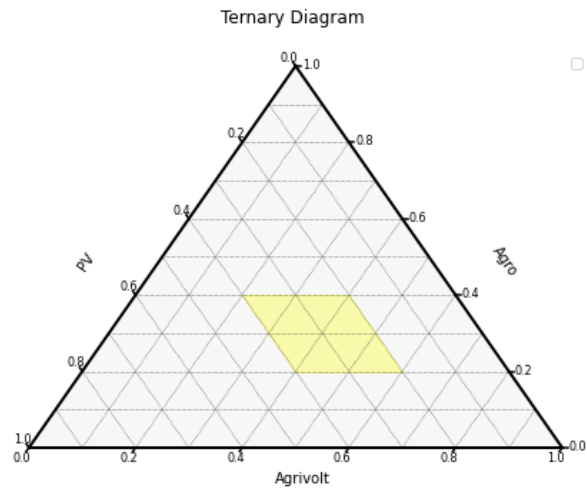
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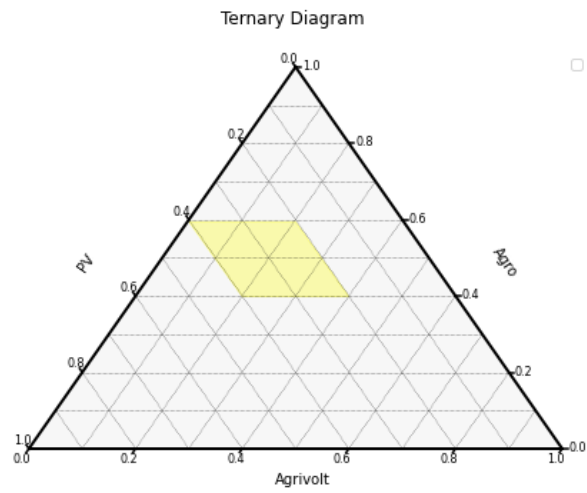
6. $0.20 \leq PV \leq 0.40$ et $0.0 \leq Agro \leq 0.2$



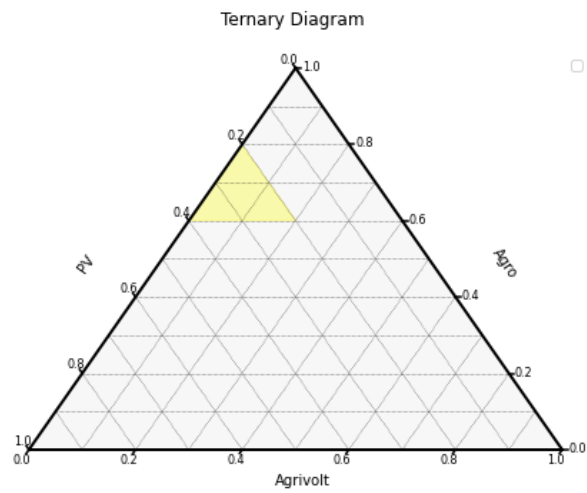
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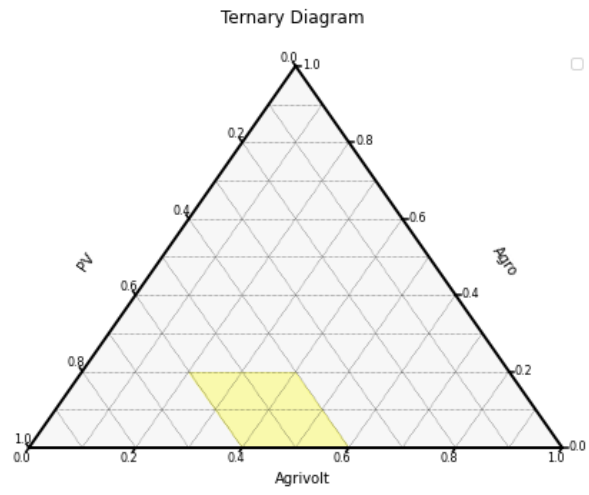
8. $0.20 \leq PV \leq 0.40$ et $0.4 \leq Agro \leq 0.6$



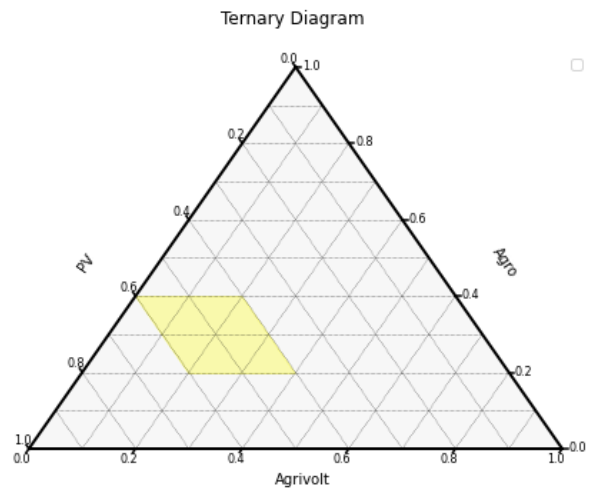
9. $0.20 \leq PV \leq 0.40$ et $0.6 \leq Agro \leq 0.8$



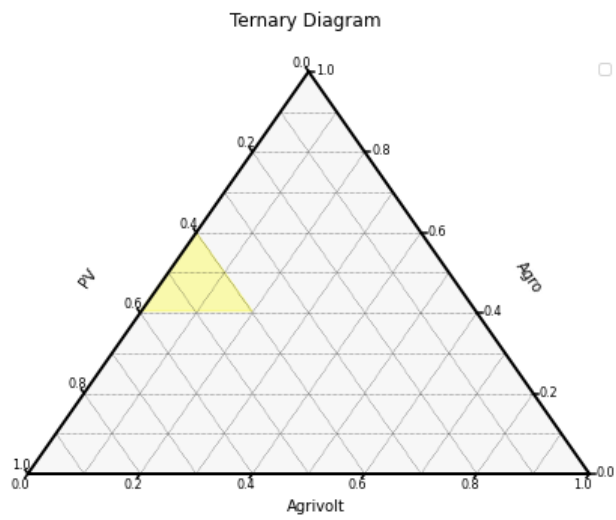
10. $0.40 \leq PV \leq 0.60$ et $0.0 \leq Agro \leq 0.2$



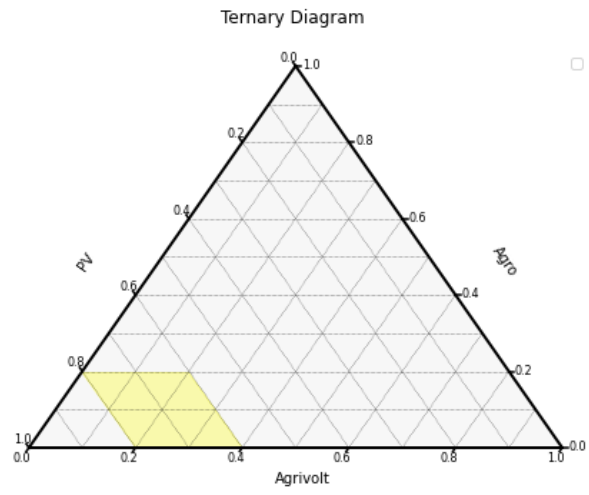
11. $0.40 \leq PV \leq 0.60$ et $0.2 \leq Agro \leq 0.4$



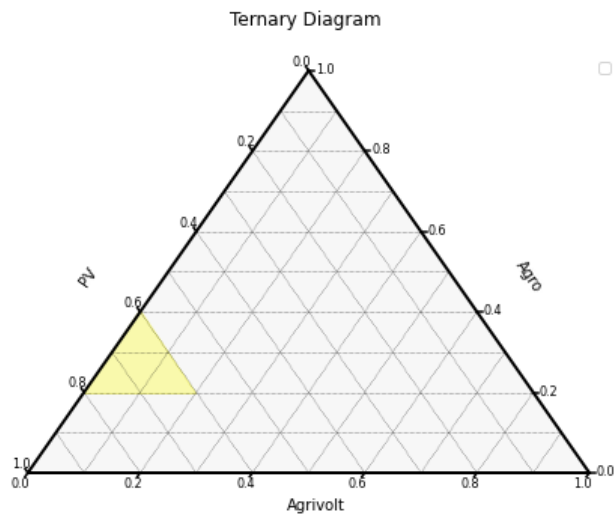
12. $0.40 \leq PV \leq 0.60$ et $0.4 \leq Agro \leq 0.6$



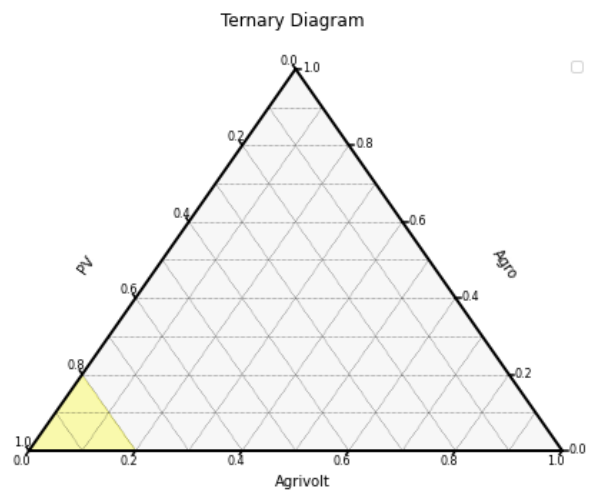
13. $0.60 \leq PV \leq 0.80$ et $0.2 \leq Agro \leq 0.4$



14. $0.60 \leq PV \leq 0.80$ et $0.2 \leq Agro \leq 0.4$



15. $0.80 \leq PV \leq 1$ et $0.0 \leq Agro \leq 0.2$



c. Appendix C: Crops' technical itineraries costs

Crop's technical itineraries costs [€/ha]	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Orchards	2259.24	2304.42	2350.51	2397.52	2445.47	2494.38	2544.27	2595.16	2647.06	2700.00
Rapeseed	443.48	452.35	461.40	470.62	480.04	489.64	499.43	509.42	519.61	530.00
Durum wheat	451.85	460.88	470.10	479.50	489.09	498.88	508.85	519.03	529.41	540.00
Maize - early maturing	652.67	665.72	679.04	692.62	706.47	720.60	735.01	749.71	764.71	780.00
Maize - late maturing	669.40	682.79	696.45	710.38	724.58	739.08	753.86	768.94	784.31	800.00
Maize silage	669.40	682.79	696.45	710.38	724.58	739.08	753.86	768.94	784.31	800.00
Pea	276.13	281.65	287.28	293.03	298.89	304.87	310.97	317.19	323.53	330.00
Grassland	200.00	205.00	211.00	217.00	222.00	228.00	234.00	240.00	246.00	253.00
Meadow	200.00	205.00	211.00	217.00	222.00	228.00	234.00	240.00	246.00	253.00
Soy	276.13	281.65	287.28	293.03	298.89	304.87	310.97	317.19	323.53	330.00
Sunflower seed	351.44	358.47	365.64	372.95	380.41	388.02	395.78	403.69	411.76	420.00
Hay	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

d. Appendix D: Crops' selling prices

Crops' selling prices [€/ha]	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Soy	192.45	196.30	200.23	204.23	208.32	212.48	216.73	221.07	225.49	230.00
Durum wheat	92.04	93.88	95.76	97.68	99.63	101.62	103.66	105.73	107.84	110.00
Rapeseed	209.19	213.37	217.64	221.99	226.43	230.96	235.58	240.29	245.10	250.00
Maize - early maturing	78.24	79.80	81.40	83.03	84.69	86.38	88.11	89.87	91.67	93.50
Maize - late maturing	71.12	72.55	74.00	75.48	76.99	78.53	80.10	81.70	83.33	85.00
Maize silage	78.24	79.80	81.40	83.03	84.69	86.38	88.11	89.87	91.67	93.50
Pea	117.15	119.49	121.88	124.32	126.80	129.34	131.93	134.56	137.25	140.00
Sunflower	200.82	204.84	208.93	213.11	217.38	221.72	226.16	230.68	235.29	240.00
Meadow	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orchards	916.25	934.57	953.26	972.33	991.78	1011.61	1031.84	1052.48	1073.53	1095.00

e. Appendix E: Irrigation costs

Irrigation costs [€]	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Hose reels 12	224.25	228.74	233.31	237.98	242.74	247.59	252.54	257.59	262.75	268.00
Hose reels 25	256.05	261.17	266.39	271.72	277.15	282.70	288.35	294.12	300.00	306.00
Integral	162.33	165.58	168.89	172.27	175.71	179.23	182.81	186.47	190.20	194.00
Center pivot	204.17	208.25	212.42	216.67	221.00	225.42	229.93	234.53	239.22	244.00
Drip	570.67	582.08	593.72	605.60	617.71	630.06	642.66	655.52	668.63	682.00

f. Appendix F: Water taxes

Water taxes	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Groundwater [€/m2]	54.39	55.48	56.59	57.72	58.87	60.05	61.25	62.48	63.73	65
Surface water [€/ha]	1.42	1.45	1.48	1.51	1.54	1.57	1.60	1.63	1.67	1.7
Reservoir [€/m3]	1.26	1.28	1.31	1.33	1.36	1.39	1.41	1.44	1.47	1.5

g. Appendix G: Crop's caloric and protein contents

Crop	Proteins content [ratio]	Energy content [Kcal/Kg]
Durum wheat	0.16	4420.00

Meadow	0.08	4278.20
Rapeseed	0.20	6940.00
Maize silage	0.08	4421.61
Pea	0.23	4370.00
Maize	0.09	4450.00
Sunflower seed	0.16	6850.00
Hay	0.08	4344.10
Orchards	0.03	520.00
Soy	0.37	4460.00

h. Appendix H: Crops' environmental impact scores

Crop	Impact [μ Pt]
Durum wheat	103.64
Meadow	-26.23
Rapeseed	221.21
Maize silage	116.87
Pea	71.34
Maize	116.87
Sunflower seed	220.64
Hay	0
Orchards	367.74
Soy	197.75

i. Appendix I: Renewable energy units' environmental impact scores

Technology	Impact [Pt]
Solar panel	0.33
Wind turbine	188

Chapter 4: Generation of multi-actor water-energy-food nexus scenarios: Multi-objective optimization

I. Introduction

This chapter presents the second approach designed to develop strategic decision-making methods for our multi-actor multi-level framework conceived for WEFN systems. The second approach is based on multi-objective optimization. It has been conceived for land-use allocation problems. The approach is tested on the same case study territory as the one used to illustrate the first strategic decision-making approach presented in the previous chapter. The case study territory is the downstream part of the French Aveyron river's watershed located south of France. It accounts with around 15000 agricultural parcels. Three land-use alternatives are considered for each parcel. Ten multi-criteria performance indicators are used as objectives of the multi-objective optimization problem. Mixed Integer Linear Programming (MILP) and goal programming are combined to model and solve the multi-objective land-use allocation problem with IBM's ILOG CPLEX optimization studio.

The exploratory stochastic strategic decision-making approach presented in the previous chapter has chronologically been designed first to ensure models that find resource management solutions for large size problems (territories with around 15000 parcels and 10 multi-criteria performance indicators). The optimization strategic decision-making approach presented in this chapter has been implemented to test the use and efficiency of a multi-objective deterministic approach that is more similar to traditional PSE (Process and Systems Engineering) approaches. For instance, Nie et al. (2019) have formulated a multi-objective optimization problem as a MINLP problem to find land management strategies characterized by optimal percentages of different land uses. Uslu et al., (2021) have modelled a multi-objective optimization problem to find regional optimized resource allocation schemes for five farmers characterized by groundwater and surface water use and crop and fertilizer choices. Cheng et al. (2023) have modelled an agricultural land management problem as a spatial multi-objective optimization problem to find optimal surface areas of varied agricultural crops. Water use minimization and economic maximization objectives are considered. Agrawal et al. (2024) have modelled a cropland occupancy problem as a multi-objective mixed integer linear program to find land occupancies fractions for distinct crops. The problem considers food and bioenergy production maximization and water consumption minimization objectives at regional level. Sun et al. (2024) have modelled a multi-objective optimization problem to obtain the Pareto front of crop cover percentages solutions that optimize water use, carbon sequestration and economic benefits of a Chinese farm. We have chosen to model our problem as a MILP problem because it allocates land-use alternatives taken from a set of known land-use alternatives at parcel level. Goal programming is used to solve the problem because implementing epsilon-constraint to find Pareto fronts with ten objectives is not

manageable. Moreover, a sensibility analysis on the objectives and the present expert knowledge has enabled the definition of coherent goals needed for the methodology to converge under most scenarios of different objective weights combinations.

The chapter is structured as follows. The methodology underlying the approach is displayed and explained first. Then, the case study territory and case study parameters are described. Results are shared in a results section and discussed in a discussion section. A conclusion and perspectives section concludes the chapter.

II. Strategic decision-making multi-objective optimization approach for our multi-level multi-actor WEFN framework

a. Generic multi-objective strategic decision-making approach

This section describes the generic multi-objective strategic decision-making approach designed to develop strategic decision-making methods for our multi-actor multi-level framework for WEFN systems. The aim of the strategic decision-making method created with this approach is to produce a single optimized management scenario of water, energy and food resources that satisfies multi-actor and multi-criteria constraints and objectives. Figure 1 illustrates the multi-actor multi-level framework implemented with a strategic multi-objective decision method.

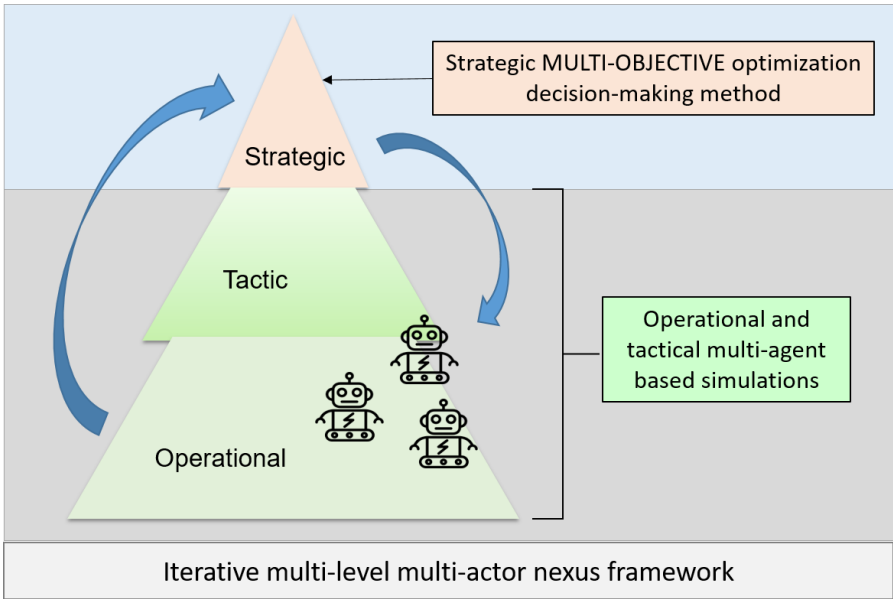


Figure 1: Multi-actor multi-level framework for WEFN systems with a strategic multi-objective decision-making method

The framework illustrated in Figure 1 iterates between decision levels. The strategic decision-making method relies on spatial and temporal data produced by operational and tactical multi-agent based simulations that simulate nexus systems dynamically. Operational and tactical data is processed into performance indicators that constitute objectives of the multi-objective optimization method. In such a way, the strategic multi-objective method generates

an optimal scenario that satisfies operational and tactical constraints. The optimal strategic scenario produced describes systems at fine spatial and temporal scales. The multi-actor multi-level framework implemented with a strategic multi-objective optimization decision-making method solves nexus land-use allocation problems by finding a combination of parcel land-use allocations that optimizes regional performance indicators. Figure 2 illustrates a nexus land-use allocation problem for which land-use alternatives must be allocated at parcel level for an entire agricultural watershed territory. For instance, three land-use alternatives can be allocated to parcel P1 in Figure 2. This is the case for all parcels of the entire territory considered. The multi-objective optimization strategic decision-making method must find the combination of land-use alternatives on parcels that optimizes territory performance indicators.

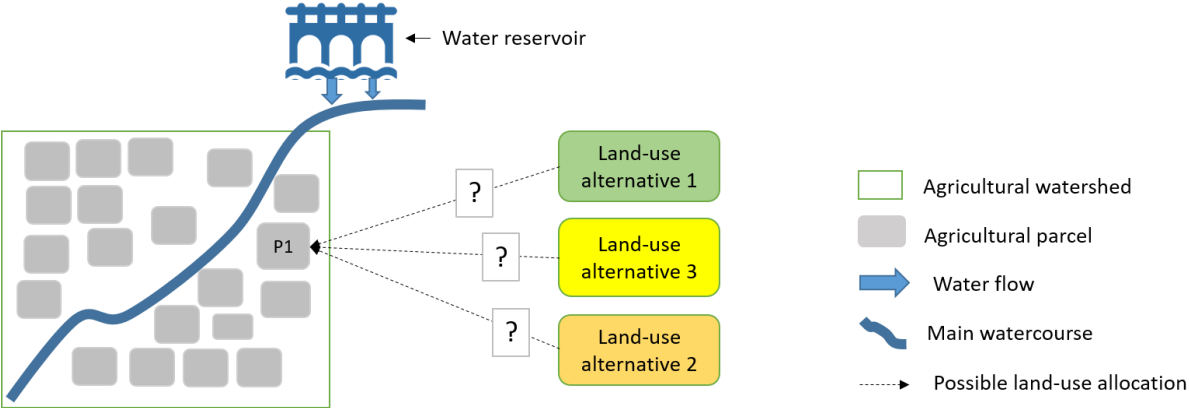


Figure 2: Illustration of a land-use allocation problem in agricultural land

Figure 3 depicts the methodological steps that need to be followed to implement our multi-level multi-actor WEFN framework for land-use allocation problems using strategic multi-objective regional decision-making methods. The workflow shown in Figure 3 is the same as the one needed to implement our framework with multi-criteria strategic decision-making methods introduced in Chapter 3. The only step that changes is the last step, which implements decision-making methods. Contrary to the previous chapter, only a regional, no local, multi-objective optimization approach is designed.

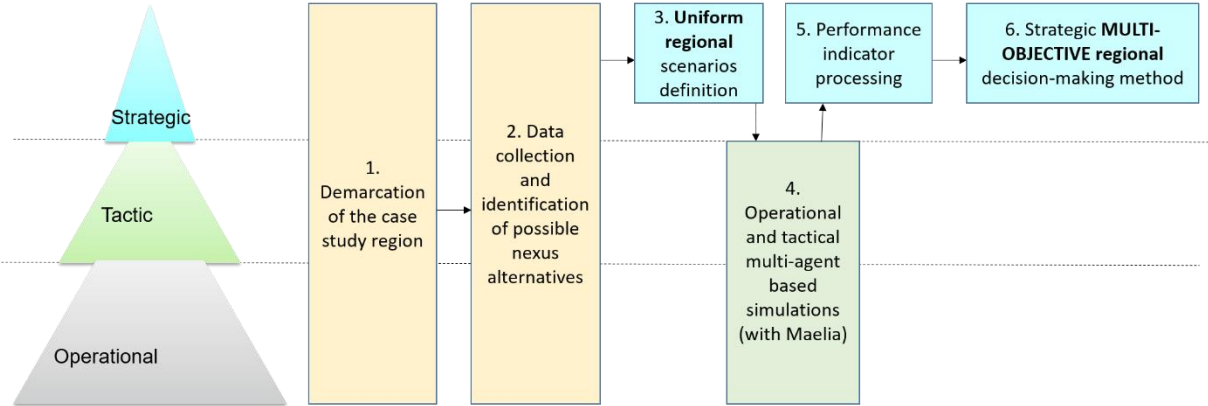


Figure 3: Generic methodological steps to lead a multi-level multi-actor approach for water-energy-food nexus land allocation problems in agricultural territories with strategic multi-objective decision-making methods

The multi-objective optimization approach described below has been conceived for large size multi-objective land-use allocation problems (ex: territories of around 15000 spatial entities and 10 objectives). The land-use allocation problem is conceptualized as a mixed integer linear program (MILP) and goal programming is used to solve the multi-objective problem. Goal programming has been preferred over the classical epsilon constraint method because epsilon constraint method for large size problems as the one addressed here is not conceivable.

b. Mixed integer linear programming formulation

The land-use allocation problem is conceptualized as a MILP problem with n binary variables where n equals the product of the number of spatial entities considered in the case study territory times the number of land-use alternatives considered for each spatial entity. Objective values of each objective of the multi-objective optimization problem are known at spatial entity level under each land-use alternative and constitute the input data of the problem. For objectives that only have a meaning at territory level, a mean spatial entity value is associated to each spatial entity by dividing the territory value by the total number of territory spatial entities. Territory level objectives constitute the variables of the MILP model. They are computed with Equation 1. The value of territory objective i equals the sum of values of objective i of every spatial entity of the territory.

Equation 1: Objective i at territory scale

$$Objective\ i_{territory} = \sum_{j=1}^{nb\ of\ entities} Objective\ i_{entity\ j}$$

To link binary variables to input data equation 2 is written as a constraint for each spatial entity considered.

Equation 2: Objective i at spatial entity scale

$$Objective\ i_{entity\ j} = \sum_{k=1}^{nb\ of\ alternatives} Y_{alternative\ k_{entity\ j}} * Objective\ i_{Y_{alternative\ k_{entity\ j}}}$$

Equation 3, which translates the fact that only and at least one land-use alternative is allocated to every spatial entity of the territory considered, is considered as an additional constraint.

Equation 3: Constraint on binary values for every spatial entity

$$\sum_{k=1}^{nb\ of\ alternatives} Y_{alternative\ k_{entity\ j}} = 1, \quad Y_{alternative\ k_{entity\ j}} \in \{0,1\}$$

c. Mono-objective optimizations to validate the approach

Mono-objective optimizations are run to validate the approach. Running a mono-objective optimization for each performance indicator set as an objective enables validating the

approach by evaluating on the one side if the model converges and on the other side if the local optimal found with each mono-objective optimization resembles the scenario expected from expert knowledge. IBM optimization studio's CPLEX solver is used to solve the mono-objective optimizations. CPLEX solver implements the simplex algorithm in C.

d. Goal definition and sensibility analysis

To verify that a coherent goal (or utopia point, see paragraph e. below) is defined for the goal programming formulation, a sensibility analysis of the criteria used as objectives of the multi-objective problem is lead. The aim of this sensibility analysis is to analyse how the criteria are affected by varying inputs, in our case, by distinct land-use allocation scenarios. Bi-criteria graphs are plotted to examine such behaviours and to identify trade-offs between objectives. Criteria goal values are defined from expert knowledge or through mono-objective optimizations and all combined they form the goal of the goal programming model. Criteria goals are plotted on the bi-criteria graphs to verify that they represent optimal points.

e. Goal programming to solve a multi-objective optimization problem

Goal programming is used to solve the multi-objective land-allocation optimization problem. Goal programming converts a multi-objective problem into a single objective problem. The objective is a weighted sum of deviations where the deviations are the differences between objective values of a solution being examined and objective values of a reference goal point named the utopia point. Figure 4 illustrates the goal ($goal_i$) and the deviations (d_i) between the goal and the solution being examined ($f_i(x)$).

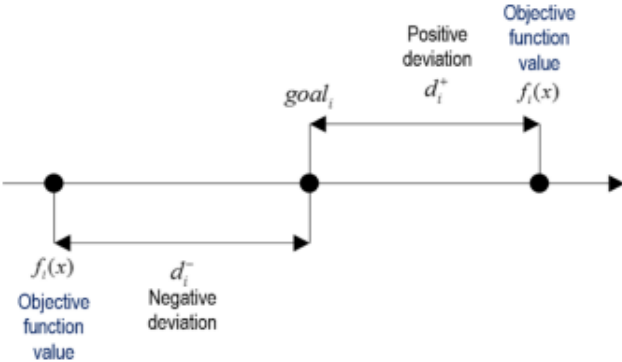


Figure 4: Illustration of the deviations and goal of a goal programming problem (taken from (Ramos et al., 2014))

Equation 4 shows the objective of the goal programming model, that aims at minimizing deviations between the objective function values and the goal values, and the equalities and inequalities that constrain solutions of the goal programming model. Goals and objective function values are normalised to solve for the solutions. See (Ramos et al., 2014) for a more detailed mathematical description of the goal programming method.

$\min \sum w_i * \{d_i^+ \vee d_i^- \vee d_i^+ + d_i^-\}$, subject to:

$$f_i(x) + d_i^- + d_i^+ = goal_i, \quad \forall i \in F$$

$$d_i^-, d_i^+ \geq 0, \quad \forall i \in F$$

$$h(x) = 0$$

$$g(x) \leq 0$$

$$x \in R^n, h \in R^p, g \in R^r$$

The goal or utopia point is a hypothetical scenario under which all objectives are at their best. Objective values of the utopia point are determined from expert knowledge or through mono-objective optimizations. For our land-use allocation problem both expert knowledge and mono-objective optimizations are used to characterize the utopia point. Objective weights are determined by expert knowledge or with statistical data. For our study, different scenarios of weights combinations are tested since at the time being stakeholders of the system have not been consulted to agree upon objectives' relative importance.

III. Case study

a. Territory of around 15000 agricultural parcels and study period

The case study territory selected to illustrate the strategic multi-objective optimization decision-making approach presented in this chapter is the same territory as the one used to illustrate the strategic Monte Carlo based decision-making approach presented in Chapter 3. The case study territory is the downstream part of the Aveyron's watershed located south of France (see Figure 10 of Chapter 3). It is a territory of about 800km² split into 15224 agricultural parcels. 16061 parcel entities are derived when the layer of agricultural parcels is superposed with the layer of SAFRAN's meteorological polygons. Three land-use allocation alternatives are considered for each parcel entity. The first one is a 100% Agro alternative under which a parcel entity's surface is entirely covered with agricultural crops. The second one is an Agrivoltaics alternative under which 30% of a parcel entity's surface that is suitable for solar panels is covered with PVs and the rest of the surface is covered with agricultural crops. The third one is a 100% PV land-allocation alternative under which all the surface of a parcel entity that is suitable for solar panels is covered with PVs and the rest with agricultural crops. The number of binary variables of the MILP land-allocation problem for this case study territory is equal to 3*16061 = 48183. Wind turbine alternatives are not considered in the territory because only 0.85% of its agricultural area is suitable for wind turbines and Energy Payback Times are too long (from 3 to 7 years, see Figure 13 of chapter 3).

2006-2025 is taken as the study period because the multi-agent based platform (MAELIA, see chapter 2) used to simulate operational water-food scenarios of the case study territory has

been calibrated for the 2006-2015 period. Input data is duplicated over the 2016-2025 to consider a 20 years long period since the average lifespan of solar panels is of 20 years.

b. Ten multi-criteria performance indicators as objectives

The ten multi-criteria water-energy-food nexus performance indicators established at the end of Chapter 2 are treated as objectives of the multi-objective land-use allocation optimization problem. Table 1 illustrates and explains them. They are computed over the 20-yearlong study period. All of them are computed at parcel entity level and then aggregated into a territory indicator that is used as an objective of the multi-objective optimization problem except from the water LWRF [days] indicator because it only has meaning at territory level. A mean territory indicator is associated at parcel entity level to solve the multi-objective problem with the MILP formulation introduced in paragraph II.b. above.

Table 1: 10 objectives of the multi-objective land-use allocation problem

Nb	Performance indicator - Notation	Significance
1	Agricultural energy production - Energy agro [J]	Total caloric energy derived from crops
2	Solar energy production - Energy PV [J]	Total electricity produced by solar panels
3	Food proteins production – Proteins agro [kg]	Total proteins derived from crops
4	Solar net present value – NPV PV [€]	Total solar net present value
5	Gross agricultural margin – Gross margin agro [€]	Total gross agricultural margin
6	Solar environmental impact – EF PV [mPts]	Life cycle environmental footprint score taken from Ecoinvent (“ecoinvent v3.0 - ecoinvent,” 2020)
7	Agricultural environmental impact – EF agro [mPts]	Life cycle environmental footprint score Ecoinvent (“ecoinvent v3.0 - ecoinvent,” 2020)
8	Water withdrawal indicator – Water ind	Total volume of water withdrawn for irrigation weighted by an integer associated to each water source (see Table 7 of chapter 2)
9	Duration of river flow below low-water regulating flow – LWRF [days]	Total period duration of river flow below low-water regulating flow (LWRF)
10	Number of farmer working hours – Farmer work [h]	Total hours farmers spend at work to carry out crops’ technical itineraries

c. Scenarios of multi-objective weights combinations

Six scenarios of multi-objective weights combinations are tested for the case study territory. Table 2 gives weights associated to each objective for each scenario. Scenario 0 associates equal weights (= 0.1) to all objectives. Scenario 1 associates equal weights to all objectives (= 0.1) except for water related objectives (Water ind and LWRF [days]) for which weights are null. Scenario 1 is expected to favour agricultural alternatives more than scenario 0 does since scenario 1 gives no importance to water use and agriculture alternatives are more water intensive than solar alternatives. Scenario 2 associates equal weights to all objectives (= 0.1) except for water related objectives for which weights are null and for agricultural production objectives (Energy agro [J] and Proteins agro [kg]) for which weights are higher (= 0.2). This scenario is the one that favours agricultural alternatives the most. Scenario 3 associates equal weights to all objectives (= 0.1) except for water related objectives for which weights are higher (= 0.2). This scenario is expected to favour solar alternatives with respect to scenario 0. Scenario 4 associates equal weights to all objectives (= 0.1) except for water related objectives and the solar energy production objective for which weights are higher (= 0.2). This scenario is the one that favours solar alternatives the most. Scenario 5 associates equal weights to all objectives (= 0.1) except for agricultural production objectives (Energy agro [J] and Proteins agro [kg]) for which weights are higher (= 0.2).

Table 2: Scenarios of multi-objective weights combinations

	w1 - Energy agro [J]	w2 - Energy PV [J]	w3 - Proteins agro [kg]	w4 - NPV PV [€]	w5 - Gross margin agro [€]	w6 - EF PV [mPts]	w7 - EF agro [mPts]	w8 - Water ind	w9 - LWRF [days]	w10 - Farmer work [h]
Scenario 0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Scenario 1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0	0.1
Scenario 2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0	0	0.1
Scenario 3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1
Scenario 4	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1
Scenario 5	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1

d. Software for implementation

Version 12.8.0.0 of IBM ILOG CPLEX Optimization Studio is used to solve the mono-objective and multi-objective optimization problems. IBM ILOG CPLEX Optimization Studio is installed on a computer with an Intel(R) Xeon(R) Platinum 8160 CPU @ 2.10GHz 2.10 GHz processor.

IV. Results

a. Mono-objective optimizations

A mono-objective optimization has been run for each of the ten objectives of the multi-objective land-use allocation problem. Table 3 summarizes the allocation occurrences of each of the three land-use alternatives considered for each spatial entity of our case study territory obtained from each mono-objective optimization. Table 3 shows that for seven out of the ten mono-objective optimizations run all parcels are allocated the same alternative. When solar objectives, Energy PV [J] and NPV PV [€], are maximized and when water and social objectives, Water ind, LWRF [days] and farmer work [h], are minimized all parcels are allocated a 100% PV land-use alternative. The maximization of Proteins agro [kg] and the minimization of the environmental solar impact (EF PV [mPts]) allocate a 100% agro land-use alternative on every parcel. These results go along with the expert knowledge expectations. To validate results from the other three mono-objective optimizations further analysis has been carried out.

Table 3: Allocation occurrences of land-use alternatives at parcel entity level for each mono-objective optimization

	Agro	Agrivolt	PV
max Energy agro [J]	7784	59	8218
max Energy PV [J]	0	0	16061
max Proteins agro [kg]	16061	0	0
max NPV PV [€]	0	0	16061
max Gross margin agro [€]	3	716	15342
min EF_PV [mPts]	16061	0	0
min EF_agro [mPts]	6462	408	9191
min Water ind	0	0	16061
min LWRF [days]	0	0	16061
min farmer work [h]	0	0	16061

The maximization of Energy agro [J] allocates a 100% agro land-use alternative to 7784 parcel entities, an Agrivoltaics land-use alternative to 59 parcel entities and a 100% PV land-use alternative to 8218 parcel entities. Figure 5 shows the spatial distribution of land-use allocations obtained from the maximization of Energy agro [J].

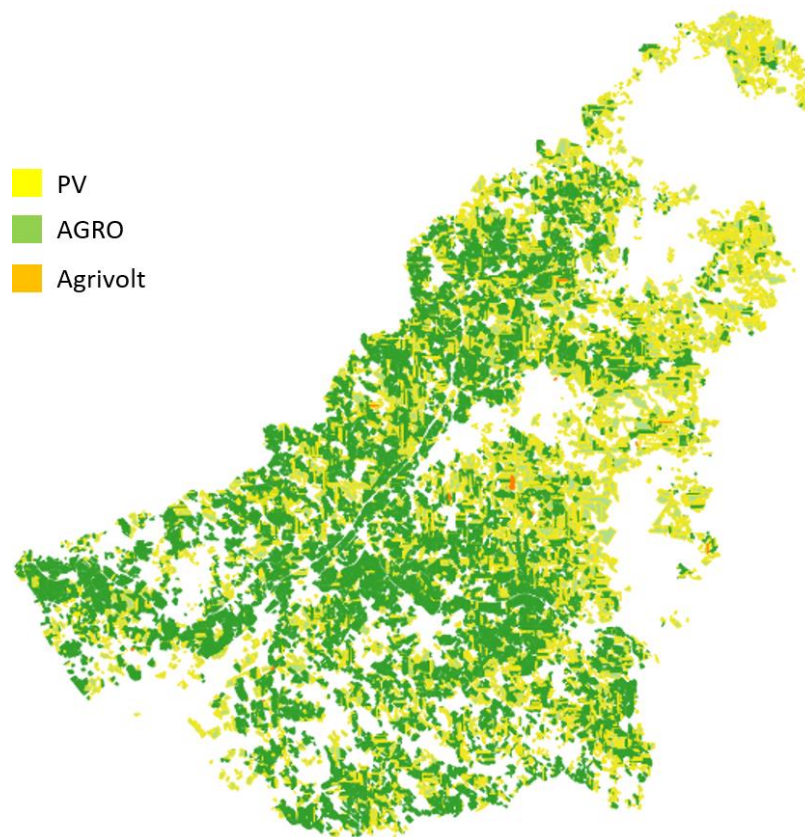


Figure 5: Spatial distribution of land-use allocations resulting from the maximization of Energy agro [J]

A data analysis has shown that all parcel entities on which the maximization of Energy agro [J] has allocated a 100% PV land-use alternative are parcel entities for which the agricultural yield is null under any land-use alternative. It is also the case for 22 out of the 59 parcel entities that have been assigned an Agrivoltaics land-use alternative. Appendix A shows agricultural surfaces of the 37 parcels that have been assigned an Agrivoltaics alternative but for which the agricultural yield is not null. Appendix A also gives the ratio between the agricultural surface of each parcel entity under an 100% agro land-use alternative and the mean parcel agricultural surface of parcel entities under an 100% agro land-use alternative (= 24360 m²). Appendix A illustrates that the 37 parcels entities examined have very small agricultural surfaces in comparison to parcel entities of the territory under study. This means that their maximum agricultural yields are very small in comparison to those of other parcel entities. The solution obtained with the maximization of Energy agro [J] is thus coherent and exemplifies the fact that the simplex algorithm finds local and not global optimal solutions. A global optimum for the above maximization allocates a 100 % agro land-use alternative on the 37 parcel entities characterized in Appendix A.

The maximization of the gross agricultural margin (Gross margin agro [€]) allocates a 100% agro land-use alternative to 3 parcel entities, an Agrivoltaics land-use alternative to 716 parcel entities and a 100% PV land-use alternative to 15342 parcel entities. Figure 6 shows the spatial distribution of land-use allocations obtained from the maximization the of gross agricultural margin.

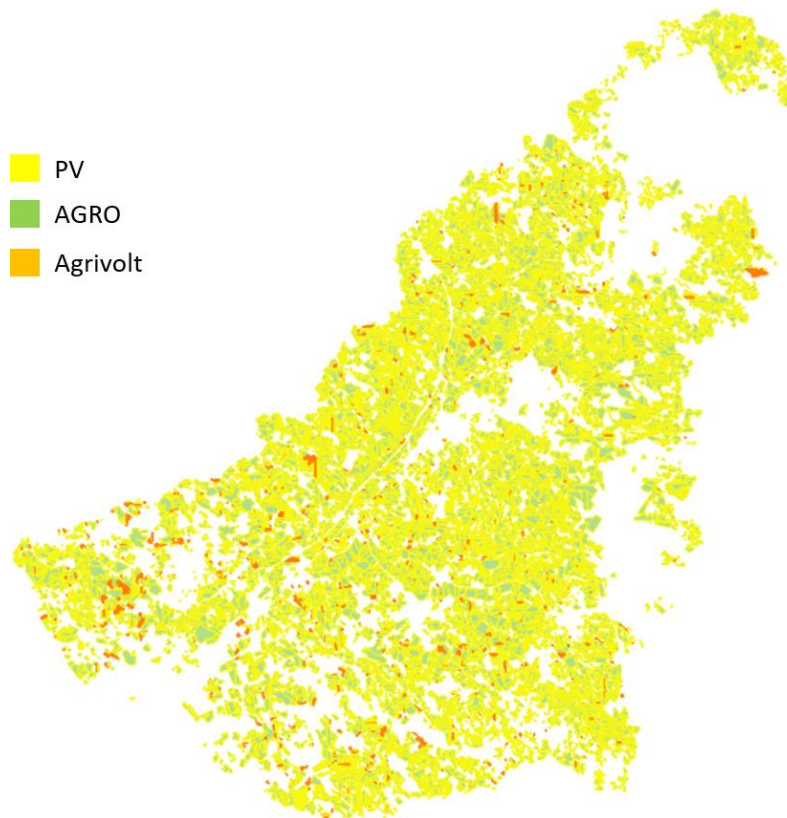


Figure 6: Spatial distribution of land-use allocations resulting from the maximization of Gross margin agro [J]

A data analysis has shown that all parcel entities on which the maximization of Gross margin agro [euros] has allocated a 100% PV land-use alternative have null or less negative agricultural gross margins than they would have under Agrivoltaics and 100% Agro land-use alternatives. Parcel entities that have been assigned Agrivoltaics land-use alternatives have null agricultural gross margins and parcel entities that have been assigned 100% agro land-use alternatives have null or positive agricultural gross margins. The solution found by the maximization of the gross agricultural margin objective is thus a global optimal.

The minimization of the agricultural environmental impact (EF agro [mPts]) allocates a 100% agro land-use alternative to 6462 parcel entities, an Agrivoltaics land-use alternative to 408 parcel entities and a 100% PV land-use alternative to 9191 parcel entities. Figure 7 shows the spatial distribution of land-use allocations obtained from the minimization of the agricultural environmental impact.

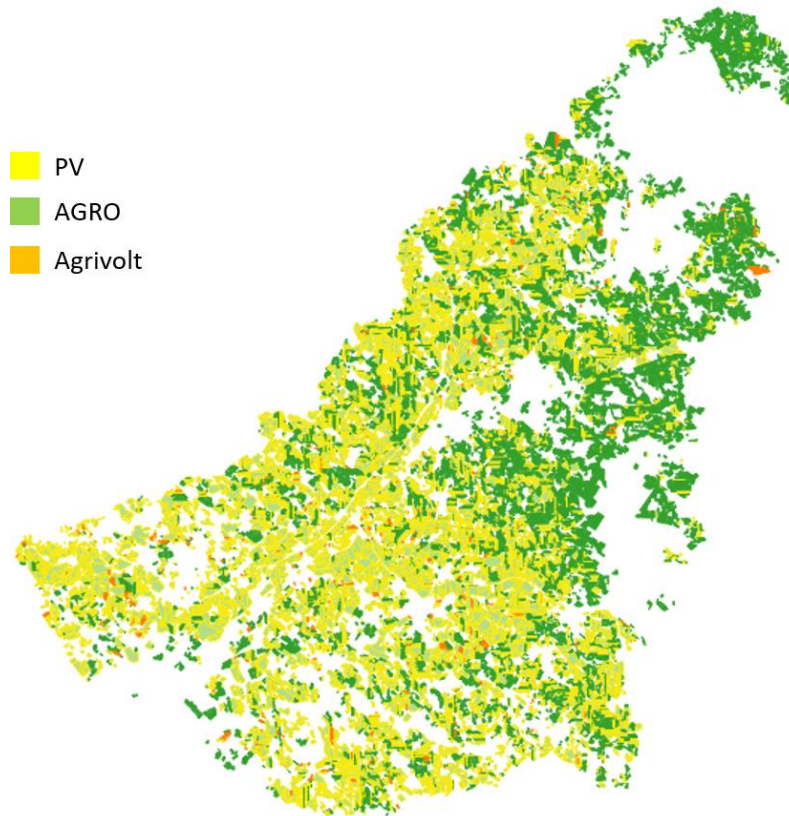


Figure 7: Spatial distribution of land-use allocations resulting from the minimization of EF agro [mPts]

A data analysis has shown that all parcel entities on which the minimization of the agricultural environmental impact has allocated a 100% PV land-use alternative produce null or positive agricultural environmental impacts. Parcel entities on which an Agrivoltaics land-use alternative has been allocated have null environmental agricultural impacts. Parcel entities on which a 100% agro land-use alternative has been allocated result in null or negative environmental agricultural impacts. The solution found by the minimization of the agricultural environmental impact objective is thus a global optimal.

All mono-objective optimizations are run in less than one minute except from Energy agro [J] and EF agro [mPts] mono-objective optimizations, which take 4 minutes to run.

b. Goal definition and sensibility analysis

Table 4 shows goal values of each of the ten performance indicators considered for the multi-objective problem implemented for the case study territory. They have been defined as minimum or maximum values from all values obtained for each of the ten mono-objective optimizations run (see Appendix B) and from indicator values that characterize the uniform regional 100% Agro and 100% PV scenarios shown in Table 9 of Chapter 3. For the first five indicators to the left of Table 4, indicator values are maximum values from the set of values considered, since the aim of the multi-objective problem is to maximize them. For the five other indicators to the right of Table 4, indicator values are minimum values from the set of values considered, since the aim of the multi-objective problem is to minimize them.

Table 4: Goal values of each of the ten performance indicators considered for our multi-objective optimization problem

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer work [h]
Goal	3.97E+16	2.58E+18	2.77E+08	4.31E+10	2.32E+06	0.00E+00	7.98E+04	4.03E+06	0.00E+00	3.35E+03

Table 5 describes seven points characterized from output data of the simulation of the reference agricultural water-food scenario simulated with Maelia for the case study territory and the use of water and food hypotheses. For each point shown in Table 5 and characterized by different percentages of territory parcel entities being allocated one of the three land-use alternatives considered at parcel entity level for our case study territory (Agrivoltaics, 100% Agro, 100%PV), three random land-use allocation scenarios are created and characterized. Performance indicator values for each point are obtained by doing the mean of the performance indicator values obtained for the three random land-use allocation scenarios created for each point.

Table 5: Description of land-use allocation points used to perform the criteria sensibility analysis

	%Agrivolt	%Agro	%PV
Point 1	80	10	10
Point 2	65	15	20
Point 3	50	20	30
Point 4	38	24	38
Point 5	25	30	45
Point 6	12	38	50
Point 7	10	25	65

Figures 8 to 16 illustrate the criteria sensibility analysis performed to validate the goal programming approach. Blue points stand for the seven points introduced in Table 5 and the orange red point represents the goal used to solve our multi-objective land-use allocation problem for the French case study territory considered. It can be noticed in Figures 8 to 16 that orange red points always constitute optimal points.

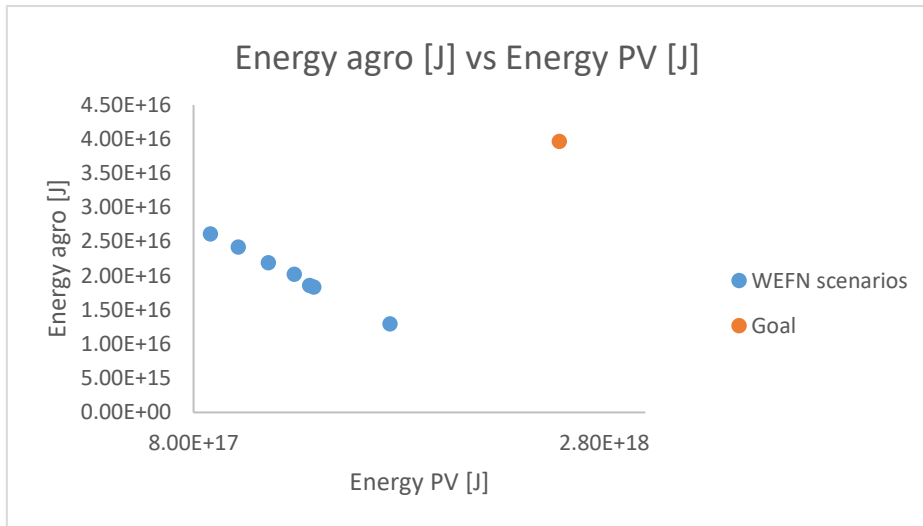


Figure 8: Bi-criteria graph of Energy agro [J] vs Energy PV [J] and Goal

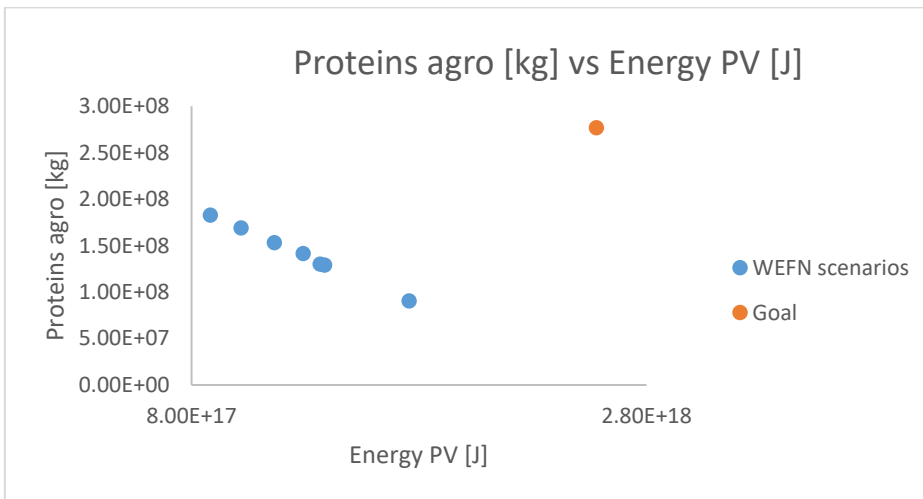


Figure 9: Bi-criteria graph of Proteins agro [kg] vs Energy PV [J] and Goal

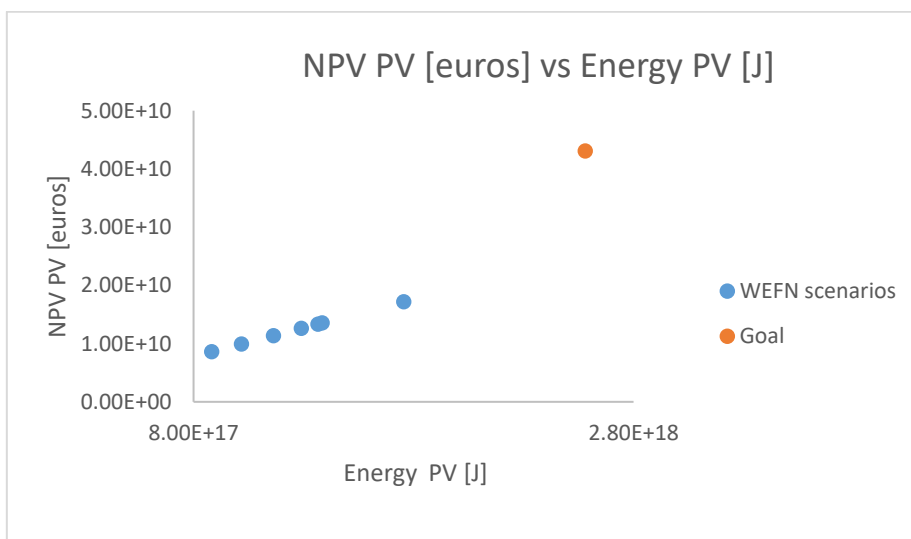


Figure 10: Bi-criteria graph of NPV PV [euros] vs Energy PV [J] and Goal

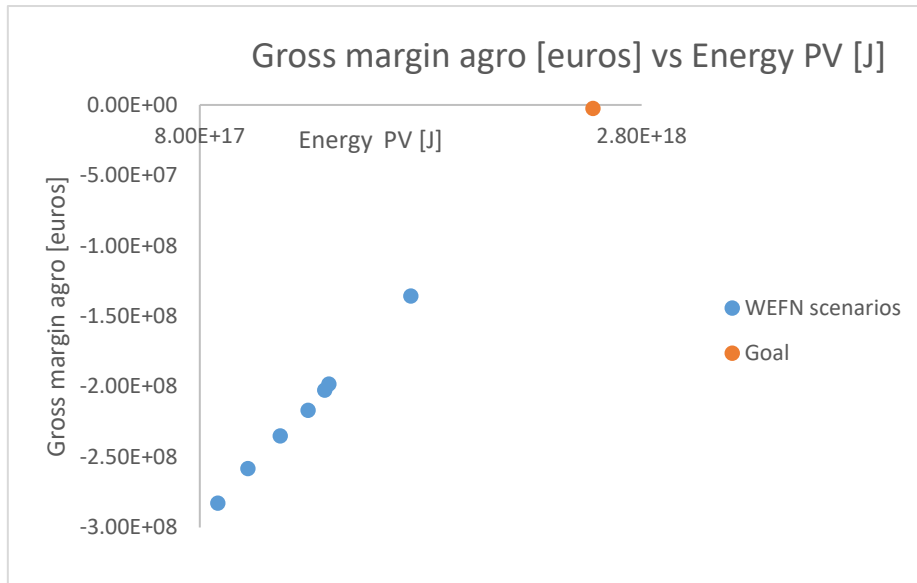


Figure 11: Bi-criteria graph of Gross margin agro [euros] vs Energy PV [J] and Goal

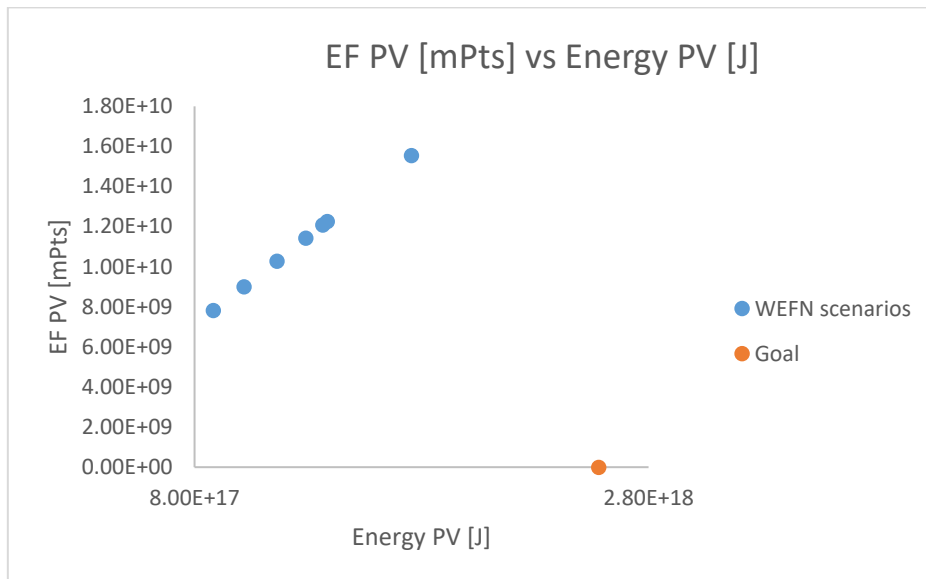


Figure 12: Bi-criteria graph of EF PV [mPts] vs Energy PV [J] and Goal

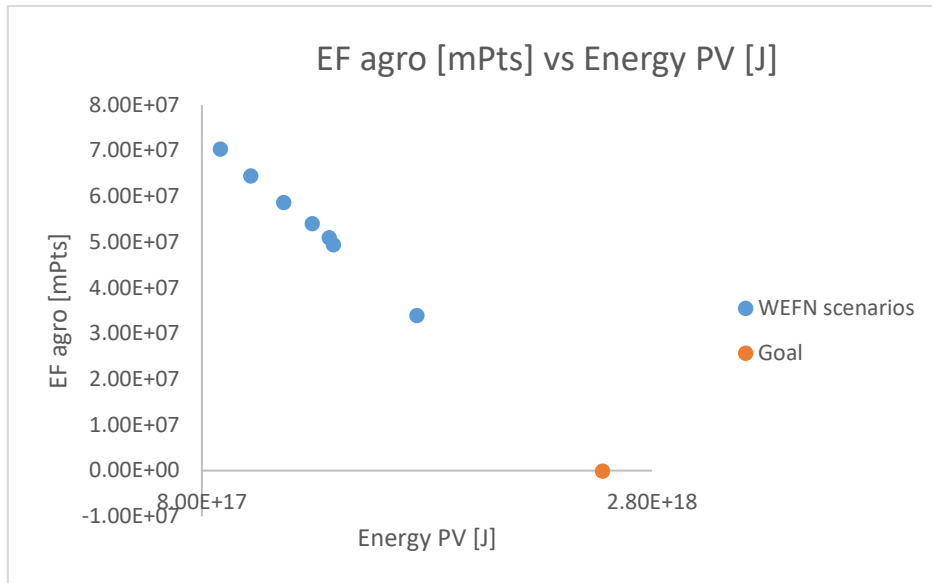


Figure 13: Bi-criteria graph of EF agro [mPts] vs Energy PV [J] and Goal

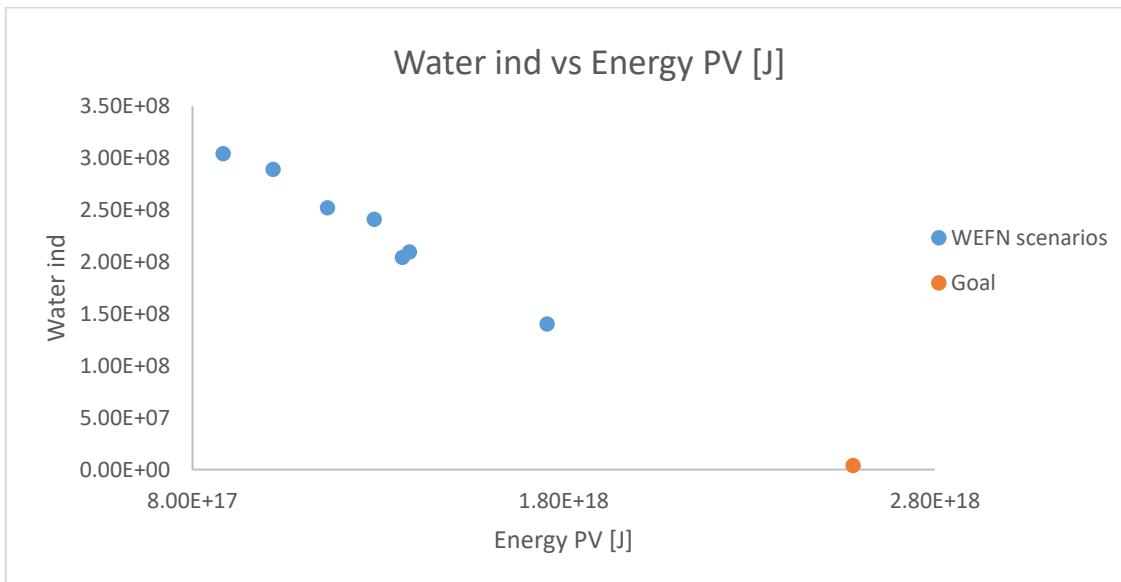


Figure 14: Bi-criteria graph of Water ind vs Energy PV [J] and Goal

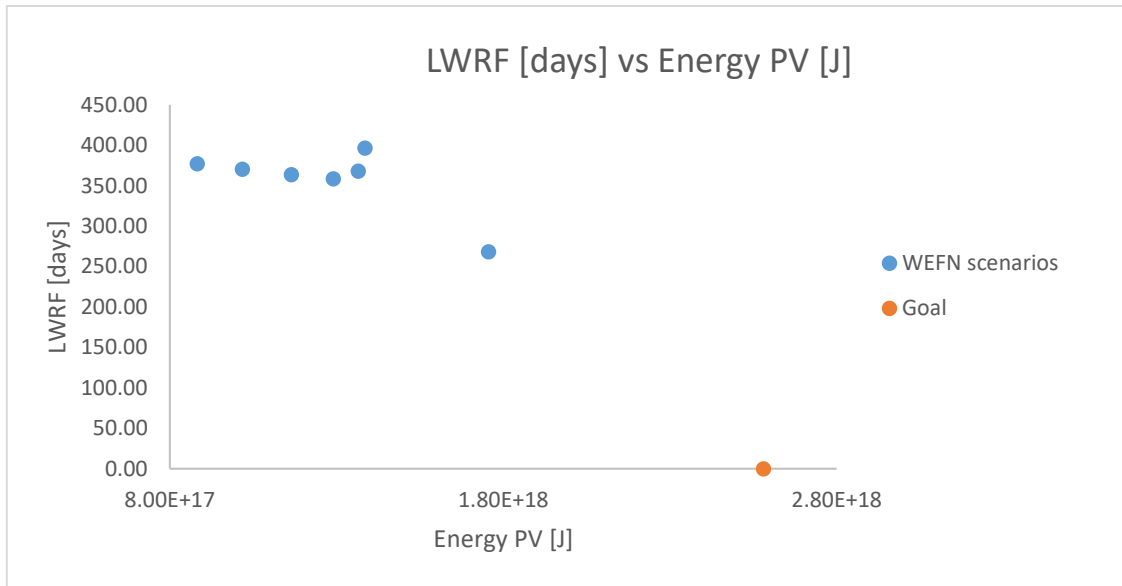


Figure 15: Bi-criteria graph of LWRF [days] vs Energy PV [J] and Goal

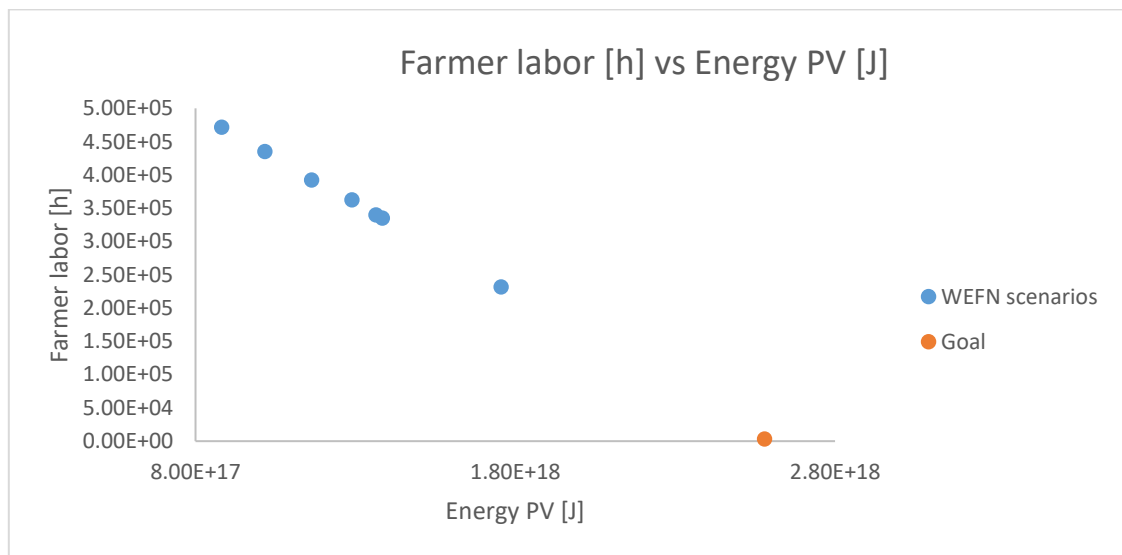


Figure 16: Bi-criteria graph of Farmer labor [h] vs Energy PV [J] and Goal

Since mono-objective optimizations have produced coherent results and since the criteria sensibility analysis has shown that the multi-criteria goal defined for the multi-objective land-use allocation problem conceptualised for our case study territory constitutes an optimal point, goal programming multi-objective optimization is implemented for our case study territory. Results are shared in section c. below.

c. Multi-objective optimization

Table 6 shows allocation occurrences of each land-use alternative at parcel entity level for each multi-objective optimization scenario considered. Scenarios 0, 1, 3 and 4 all find that allocating 100% PV alternatives on every parcel entity of the territory optimizes regional objectives. Scenario 5 has not converged because of out of memory problems. Scenario 2 produces an optimized solution that allocates a 100% PV land-use alternative to 14308 parcel

entities, an Agrivoltaics alternative to 48 parcel entities and a 100% Agro alternative to 1705 parcel entities.

Table 6: Allocation occurrences of land-use alternatives at parcel entity level for each multi-objective optimization scenario

	PV	Agrivolt	Agro
Scenario 0	16061	0	0
Scenario 1	16061	0	0
Scenario 2	14308	48	1705
Scenario 3	16061	0	0
Scenario 4	16061	0	0
Scenario 5	-	-	-

Figure 17 shows the spatial distribution of allocations of the solution produced by scenario 2. All parcels entities on which a 100% Agro land-use alternative is allocated in Figure 15 have positive agricultural energy and proteins productions as do 42 out of the 48 parcels on which Agrivoltaics land-use alternatives have been allocated. Median territory agricultural energy and proteins production values are null since 8306 parcel entities of the territory have null agricultural production potentials under the reference agricultural scenario. This explains why even under multi-objective optimization scenario 2, most parcels are allocated 100% PV land-use alternatives.

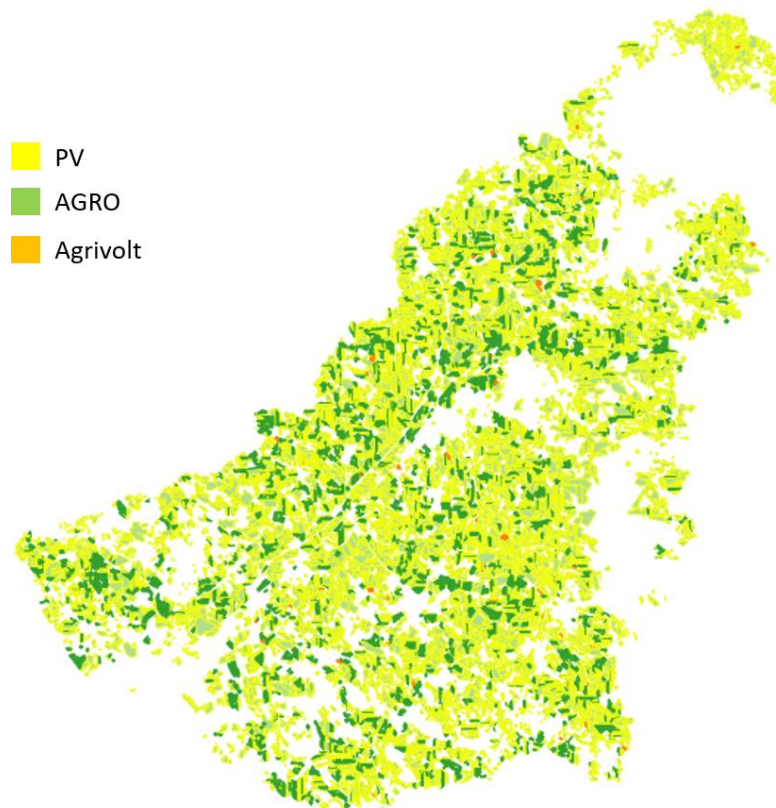


Figure 17: Spatial distribution of land-use allocations resulting from multi-objective optimization scenario 2

All scenarios are run in less than one minute except from the first scenario, which takes 13 hours and the fifth scenario, which has not converged because of out of memory problems.

V. Discussion

Running mono-objective optimizations has allowed validating the MILP model with expert knowledge and acknowledging acceptable convergence computation times. It has also inspired operational analyses of parcel level land-use allocations to understand why allocating some land-use alternatives optimizes specific territory performance indicators. Results have shown that many parcel entities have null agricultural yields and negative agricultural gross margins under the reference agricultural scenario. The minimization of the agricultural environmental impact has highlighted that some crops have a positive impact on the environment since they act as carbon sinks. Mono-objective optimizations have also illustrated that solar panels alternatives are beneficial to the water system. Results obtained from the multi-objective optimizations have shown that allocating 100% PV land-use alternatives on every parcel of the territory optimizes territory performance indicators. Only scenario 2, whose weights favour the most agricultural alternatives, has allocated 100% Agro and Agrivoltaics land-use alternatives on some parcel entities. However, covering an entire agricultural watershed with solar panels is not viable. As for results obtained from applying the strategic multi-criteria decision-making methods in chapter 3, it would be interesting to see how results are affected when governmental agricultural subsidies are considered. Additionally, including a social indicator that accounts for energy related actors' labour is another perspective, since the present social indicator only accounts for farmers' labour.

Multi-objective optimization scenario 0 associates equal weights to the ten performance indicators considered so its result can be compared to those obtained in the previous chapter with multi-criteria strategic decision-making methods that also associate equal weights to criteria computed with the same ten performance indicators. Both multi-objective optimization scenario 0 and decision-making methods developed in the previous chapter have found that covering all parcel entities with 100% PV land-use alternatives optimizes parcel and territory performance indicators. Table 7 summarizes advantages and drawbacks of the two approaches developed in Chapters 3 and 4 to perform strategic decision-making for our multi-level multi-actor WEFN framework. Table 7 shows that the stochastic multi-criteria decision-making method based on Monte Carlo simulations always finds a convenient solution for case study territories of about 1500 parcels for which three land-use allocation alternatives are compared at parcel level. The multi-objective optimization method does not always guarantee convergence for similar problems. If the multi-objective optimization converges, both approaches have similar computation complexities and times. The multi-objective approach requires having expert knowledge to define goals of all the objectives considered. A sensitivity analysis is needed to validate the goals. Consequently, the stochastic exploratory approach is more easily applied and is applicable to a wider range of territory sizes. For case study territories whose sizes enable the deterministic multi-objective approach to converge, solutions found with the stochastic and deterministic approaches are expected to be similar.

Table 7: Advantages and drawbacks of the two strategic decision-making approaches developed for our multi-level multi-actor WEFN framework

Approach	Advantages	Drawbacks
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Multi-criteria decision-making with Monte Carlo simulations (Chapter 3)	<ul style="list-style-type: none"> - Always finds a convenient solution for territories of about 1500 parcels for which 3 land-use allocation alternatives are compared at parcel level - No expert knowledge nor sensibility analysis are needed 	An optimal solution is not guaranteed
Multi-objective optimisation (Chapter 4)	A local optimal is found if the algorithm converges	<ul style="list-style-type: none"> - A solution is not always found for large size territories of about 1500 parcels for which 3 land-use alternatives are compared at spatial entity level - If an optimal solution is found, it is the only solution produced by the methodology - Needs expert knowledge to define a coherent goal and a criteria sensibility analysis to validate the goal

VI. Conclusion and perspectives

To conclude, this chapter has implemented a multi-objective optimization approach to perform decision-making based on ten strategic performance indicators defined for WEFN systems. The approach conceptualizes the WEFN system as a MILP problem and relies on goal programming and IBM's ILOG CPLEX optimization studio to solve the multi-objective problem. Goal programming has been used for our case study territory because a criteria sensibility analysis has validated the goal defined from available expert knowledge. The methodology has converged for four out of five scenarios of different objective weights combinations tested. Scenario 5, which gives more importance to agricultural production indicators and removes importance from water related indicators, has not converged. This illustrates the limit of the approach, which is only recommended for smaller size territories than the one used to illustrate our work. Results from the deterministic multi-objective optimization approach validate those found with the stochastic multi-criteria decision-making approach detailed in Chapter 3. For our case study territory, when equal importance is given to all performance indicators, covering all agricultural land that is suitable for solar panels with solar panels optimizes parcel and territory performance indicators. Since covering an entire traditional agricultural watershed territory with solar panels is not viable, simulations that consider governmental agricultural subsidies should be considered. An additional social indicator that accounts for labour of energy related actors could also be included.

A common limit of the two strategic decision-making approaches implemented in chapters 3 and 4 is that they rely on output data from incomplete dynamic operational water-energy-

food nexus simulations since the multi-agent based model (MAELIA) used to simulate the multi-actor systems at operational scale simulates water-food interactions but does not simulate energy related interactions. Chapter 5 presents an extended version of MAELIA. The extension of the platform simulates the operational impact the installation of renewable energy generation units has on water flow rates of main watercourses. One can expect that if solar panels and wind turbines are installed near the river source, parcels situated farther away from the water source and closer to the river mouth will see their agricultural yield increase or their irrigation volumes decrease. The extended version of the platform simulates the alleviation of farmers' working hours. Indicators that characterize Agrivoltaics and 100% PV land-use alternatives are computed from operational data, rather than through simplifying hypotheses as it was the case to evaluate performance indicators of energy related land-use alternatives in Chapters 3 and 4. Chapter 5 presents the extended version of the platform and analyses the variation of performance indicators computed with the two distinct versions of MAELIA, the multi-agent based platform used for the case study territory.

VII. Appendices

- a. Appendix A: Analysis of the size of agricultural surfaces on which the maximization of Energy agro [J] has allocated Agrivoltaics alternatives and on which the agricultural yield is not null

surf_agro [m2]	Ratio of surf_agro [m2] over the mean parcel agricultural surface (24360 m2)
43.01	0.002
88.75	0.004
7.88	0.000
21.26	0.001
15.03	0.001
8.07	0.000
11.84	0.000
6.88	0.000
5.30	0.000
18.99	0.001
38.93	0.002
13.40	0.001
8.48	0.000
44.51	0.002
315.05	0.013
158.36	0.007
243.16	0.010
253.90	0.010
263.77	0.011
366.47	0.015
413.29	0.017
102.89	0.004
109.55	0.004
7.37	0.000

5.60	0.000
37.92	0.002
0.30	0.000
204.04	0.008
316.88	0.013
0.53	0.000
15.53	0.001
76.07	0.003
144.24	0.006
3.46	0.000
22.19	0.001
121.67	0.005
44.56	0.002

b. Appendix B: Criteria values obtained for each of the ten mono-objective optimizations performed for our case study territory

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer work [h]
max Energy agro [J]	3.97E+16	1.14E+18	2.77E+08	1.91E+10	4.14E+08	1.02E+10	1.06E+08	4.55E+08	4.53E+02	7.02E+05
max Energy PV [J]	2.09E+14	2.58E+18	1.29E+06	4.31E+10	2.33E+06	2.28E+10	4.35E+05	4.03E+06	0.00E+00	3.35E+03
max Proteins agro [kg]	3.97E+16	0.00E+00	2.77E+08	0.00E+00	4.26E+08	0.00E+00	1.06E+08	4.55E+08	9.32E+02	7.13E+05
max NPV PV [euros]	2.09E+14	2.58E+18	1.29E+06	4.31E+10	2.33E+06	2.28E+10	4.35E+05	4.03E+06	0.00E+00	3.35E+03
max Gross margin agro [euros]	2.10E+14	2.53E+18	1.29E+06	4.22E+10	2.32E+06	2.24E+10	4.47E+05	4.03E+06	1.60E+01	3.36E+03
min EF_PV [mPts]	3.97E+16	0.00E+00	2.77E+08	0.00E+00	4.26E+08	0.00E+00	1.06E+08	4.55E+08	9.32E+02	7.13E+05
min EF_agro [mPts]	2.09E+14	1.58E+18	1.29E+06	2.65E+10	8.11E+06	1.40E+10	7.98E+04	4.03E+06	3.84E+02	1.28E+04
min Water ind	2.09E+14	2.58E+18	1.29E+06	4.31E+10	2.33E+06	2.28E+10	4.35E+05	4.03E+06	0.00E+00	3.35E+03

min LWRP [days]	2.09E+14	2.58E+18	1.29E+06	4.31E+10	2.33E+06	2.28E+10	4.35E+05	4.03E+06	0.00E+00	3.35E+03
min Farmer work [h]	2.09E+14	2.58E+18	1.29E+06	4.31E+10	2.33E+06	2.28E+10	4.35E+05	4.03E+06	0.00E+00	3.35E+03

c. Appendix C: Performance indicator values of the twenty one land-use allocation scenarios characterized with outputs of Maelia and food and water hypotheses

Scenari nb	Scenari	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRP [days]	Farmer labor [h]
0	Point_1_v2	2.63E+16	8.77E+17	1.84E+08	8.59E+09	-2.84E+08	7.77E+09	7.05E+07	3.06E+08	377.18	4.76E+05
1	Point_1_v1	2.60E+16	8.82E+17	1.82E+08	8.63E+09	-2.81E+08	7.81E+09	7.04E+07	3.02E+08	377.18	4.70E+05
2	Point_1_v0	2.61E+16	8.87E+17	1.82E+08	8.68E+09	-2.83E+08	7.85E+09	7.03E+07	3.05E+08	377.21	4.69E+05
3	Point_2_v0	2.45E+16	1.01E+18	1.71E+08	9.91E+09	-2.59E+08	8.97E+09	6.48E+07	2.88E+08	370.56	4.41E+05
4	Point_2_v2	2.43E+16	1.02E+18	1.69E+08	9.97E+09	-2.61E+08	9.02E+09	6.43E+07	2.93E+08	370.53	4.33E+05
5	Point_2_v1	2.39E+16	1.02E+18	1.67E+08	1.00E+10	-2.54E+08	9.04E+09	6.44E+07	2.87E+08	370.56	4.31E+05
6	Point_3_v2	2.17E+16	1.16E+18	1.53E+08	1.13E+10	-2.35E+08	1.02E+10	5.88E+07	2.53E+08	363.88	3.91E+05
7	Point_3_v0	2.19E+16	1.16E+18	1.52E+08	1.14E+10	-2.35E+08	1.03E+10	5.85E+07	2.48E+08	363.91	3.90E+05
8	Point_3_v1	2.22E+16	1.17E+18	1.54E+08	1.14E+10	-2.35E+08	1.04E+10	5.88E+07	2.56E+08	363.88	3.96E+05
9	Point_4_v2	2.01E+16	1.29E+18	1.41E+08	1.26E+10	-2.13E+08	1.14E+10	5.37E+07	2.31E+08	358.54	3.59E+05
10	Point_4_v0	2.02E+16	1.29E+18	1.40E+08	1.26E+10	-2.18E+08	1.14E+10	5.43E+07	2.49E+08	358.54	3.62E+05
11	Point_4_v1	2.04E+16	1.29E+18	1.43E+08	1.27E+10	-2.19E+08	1.15E+10	5.42E+07	2.44E+08	358.54	3.66E+05
12	Point_5_v1	1.88E+16	1.35E+18	1.32E+08	1.32E+10	-2.06E+08	1.20E+10	5.14E+07	2.09E+08	368.33	3.45E+05
13	Point_5_v2	1.85E+16	1.36E+18	1.29E+08	1.33E+10	-2.00E+08	1.21E+10	5.03E+07	2.00E+08	368.33	3.37E+05
14	Point_6_v0	1.85E+16	1.37E+18	1.30E+08	1.34E+10	-2.01E+08	1.21E+10	4.88E+07	2.26E+08	396.74	3.35E+05
15	Point_6_v2	1.87E+16	1.38E+18	1.31E+08	1.35E+10	-1.99E+08	1.22E+10	5.05E+07	2.03E+08	396.74	3.40E+05

16	Point _5_v0	1.85E+1 6	1.38E+ 18	1.29E+08	1.35E+1 0	-2.01E+08	1.23E+ 10	5.12E+0 7	2.05E +08	368.33	3.38E+05
17	Point _6_v1	1.79E+1 6	1.40E+ 18	1.26E+08	1.37E+1 0	-1.94E+08	1.24E+ 10	4.90E+0 7	2.00E +08	396.74	3.30E+05
18	Point _7_v2	1.30E+1 6	1.75E+ 18	9.04E+07	1.71E+1 0	-1.39E+08	1.55E+ 10	3.45E+0 7	1.42E +08	268.48	2.29E+05
19	Point _7_v0	1.31E+1 6	1.76E+ 18	9.12E+07	1.72E+1 0	-1.35E+08	1.56E+ 10	3.35E+0 7	1.43E +08	268.48	2.35E+05
20	Point _7_v1	1.28E+1 6	1.76E+ 18	8.97E+07	1.72E+1 0	-1.33E+08	1.56E+ 10	3.38E+0 7	1.36E +08	268.48	2.31E+05

VIII. References

- ecoinvent v3.0 - ecoinvent, 2020. URL <https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-0/> (accessed 3.5.23).
- Ramos, M., Boix, M., Montastruc, L., Domenech, S., 2014. Multiobjective Optimization Using Goal Programming for Industrial Water Network Design. *Ind. Eng. Chem. Res.* 53, 17722–17735. <https://doi.org/10.1021/ie5025408>

Chapter 5: Operational simulations of complete Water-Energy-Food systems

I. Introduction

Chapter 5 presents an extended version of MAELIA, the multi-agent based platform used for our multi-level multi-actor framework to simulate multi-actor operational scenarios of nexus systems. The extended version has been designed to enable operational simulations of complete water-energy-food systems. It is compared with the standard version that simulates water-food systems and that was initially coupled with food and water hypotheses to characterize complete water-energy-food systems. A methodology is presented to examine the utility of the extended version. Expert scenarios are generated from data produced with the extended version of the platform.

II. Methodology

a. Extended version of MAELIA, multi-agent based platform for WEFN systems

The extended version of MAELIA enables the operational simulation of complete WEFN systems. MAELIA's multi-agent based model has been extended to allow the simulation of solar panels in agricultural land. MAELIA simulates systems at parcel level. Its extended version takes two new input variables: a list of parcels on which solar panels are installed and a list of surface ratios covered with solar panels arranged in the same order than the first list. These two new input lists are used to adjust evapotranspiration variables at parcel level. The extended version of MAELIA downscales evaporation and transpiration values of a plot under the reference agricultural scenario with the cover ratio of the plot that is covered with solar panels under solar related land-use alternatives allocations.

b. Examining the utility of the extended version of MAELIA

To examine the utility of the extended version of MAELIA, a methodology has been established to define scenarios that are simulated and evaluated both with the extended and standard versions of Maelia with the aim of comparing characterizations resulting from both evaluations. Scenarios are evaluated by computing the ten multi-criteria performance indicators established at the end of chapter 2 from simulation outputs. The three uniform regional scenarios mentioned throughout this manuscript and introduced in Table 8 of chapter 3 are simulated first. Then, WEFN scenarios that allocate one of the three land-use alternatives that correspond to the three uniform regional scenarios to parcel entities are simulated. These scenarios are characterized by percentages of the case study territory surface covered with the three distinct land-use alternatives. When three land-use alternatives can be allocated at parcel entity level, resulting WEFN land-use scenarios are represented on a ternary diagram. Each axis of the ternary diagram corresponds to a land-use alternative and one point of the diagram indicates percentages of the territory surface covered with each land-use alternative.

Since operational simulations of land-use scenarios with MAELIA take 1 to 5 days to run, a methodology that determines priority zones of the ternary diagram to explore and how these zones are explored has been established.

i. Three uniform regional scenarios

The three uniform regional scenarios allocate either 100% Agro, Agrivoltaics or 100% PV land-use alternatives to all parcel entities of the case study territories. The 100% Agro uniform regional scenario does not account with renewable energy generation units. The standard version of Maelia is enough to model the complete water-food system underlying the reference 100% Agro uniform regional scenario. The extended version of Maelia might be interesting to simulate the complete WEFN systems underlying the Agrivoltaics and 100% PV land-use alternatives at operational scales. The 100% PV uniform regional scenario is a hypothetical scenario that is not viable for traditional agricultural territories because it compromises food autonomies. However, it is interesting to consider it to analyse and compare the utility of the extended version of Maelia with respect to its standard version. Analysing the uniform Agrivoltaics regional scenario is also interesting to compare how the extended and standard versions of Maelia simulate a compromise solution between solar and food productions in every parcel entity and its effect on regional level resources' states.

ii. Priority nexus land-allocations to investigate

Priority zones to explore in a ternary diagram are established by identifying zones that are not deemed essential to explore. In our case, two zones are judged not crucial to explore. The first one is the zone situated near the 100% Agro point shown in the ternary diagram in Figure 1. This zone is judged not essential to explore because points near the 100% Agro point characterize land-use scenarios with small solar panels cover percentages, in other words, with little parcel entities covered with 100% PV or Agrivoltaics land-use alternatives. Since the extended version of MAELIA has been conceptualized to simulate solar panels in agricultural land, scenarios close to the 100% Agro uniform regional scenario under which each parcel entity is covered with a 100% Agro land-use alternative are not the ones for which the extension of the platform is most needed. The second zone that is not considered interesting is the one that contains points that characterize WEFN scenarios for which electricity, caloric and protein autonomies are not guaranteed. To determine both zones, points generated and characterized from the combination of the standard version of MAELIA that simulates water-food nexus systems with simplifying water and food hypotheses established in Chapter 3 are used. 1500 points have been generated through the implementation of the second regional decision-making method developed in Chapter 3. Points that are not Pareto with respect to the ten multi-criteria performance indicators presented in Chapter 2 are removed from the 1500 points set. Pareto points are used to determine zones of the ternary diagram that correspond to land-use scenarios that guarantee electricity and food caloric and protein autonomies. They are also used to demarcate the zone close to the 100% Agro uniform regional scenario that corresponds to scenarios under which the territory's state is similar to

its state under the 100% Agro uniform regional scenario. To demarcate this zone, a ternary diagram is drawn for each of the ten multi-criteria performance indicators established at the end of Chapter 2. Pareto points are plotted on the ternary diagrams and coloured with four distinct colours corresponding to the four quartiles of the performance indicator being explored. Points that fall into the quartile that is closest to the 100% Agro scenario demarcate the zone close to the 100% Agro uniform regional scenario that is not fundamental to explore. The zone covered with points corresponding to the quartile that is furthest away from the 100% Agro scenario and that does not overlap points that result in scenarios that do not guarantee electricity and food autonomies delineates the start of the ternary diagram zones that are explored. The demarcation of priority and not crucial zones is illustrated in the case study section for the case study territory selected to illustrate our multi-level multi-actor framework throughout this manuscript.

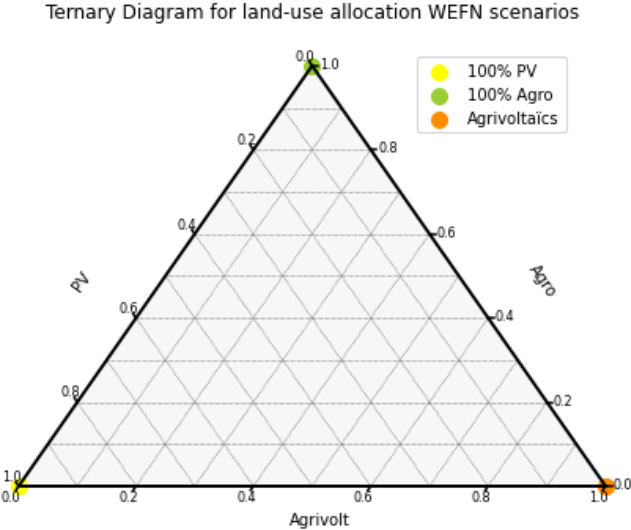


Figure 1: Ternary diagram used to characterize land-use allocation WEFN scenarios with three possible land-use alternatives for each spatial entity

iii. Exploration methodology

Once the zones that are considered important to study the use of the extended version of MAELIA have been determined, points in these zones are selected and at least three scenarios are simulated for each point. A point in the ternary diagram can correspond to distinct land-use scenarios because a point is characterized by cover territory percentages for each land-use alternative, but the selection of parcel entities that are allocated each land-use alternative can vary for two distinct scenarios corresponding to the same ternary diagram point. Points in a zone are selected according to an imaginary trajectory that crosses and spans the entire zone. The first point simulated is the one that is situated on the side of the path that is closest to the Agrivoltaics uniform regional scenario. A second point is selected on the path such as to have its cover percentages of land-use alternatives that are 5 to 15% different to those of the first point. For each point, performance indicator values are computed as a mean of those of the three scenarios simulated for that point. A third point in the path is selected in a similar

way only if the variation of water performance indicator values between the two first points simulated has varied as expected. If not, the third point is selected near the second point, with territory cover percentages of land-use alternatives that are only 5% different to those of the second point. This methodology is iterated for each of the zones of the ternary diagram that are judged necessary to explore to study the extended version of MAELIA.

c. Building expert scenarios

Expert scenarios are built with data produced from the simulation of scenarios with the extended version of MAELIA. Expert scenarios are compared to those produced with the decision-making approaches and they are plotted on the ternary diagram to situate them with respect to the zones that are judged crucial to explore to study the utility of the extended version of MAELIA. They are used to put our methodology into perspective but they are built on arbitrary objectives set by developers of the multi-actor multi-level framework designed throughout this PhD work, so they do not necessarily constitute the best scenarios for the case study territories and it is not guaranteed that they will satisfy all stakeholder's objectives.

d. Analysing spatial nexus dependencies

Two distinct scenarios that cover 50% of the suitable land to solar panels with solar panels are simulated. The first one covers 50% of the surface of every parcel entity that is suitable for solar panels with solar panels and the rest with agricultural crops. It is named the 50-50 parcel scenario. The second scenario splits the territory in two and covers the northern half with 100% PV land-use alternatives and the southern half with 100% agro land-use alternatives. It is named the 50-50 territory scenario. The idea behind exploring these two scenarios being to analyse whether installing solar panels in the northern land has positive impacts on river flow rates or agricultural yields.

III. Case study

a. Territory of around 15000 agricultural parcels and study period

The case study territory selected to examine the use of the extended version of MAELIA is the same as the one used to illustrate work presented in the previous chapters. It is an 800 km² agricultural zone situated downstream the French Aveyron river, located south of France. The agricultural territory is split into 15524 parcels (see Figure 10 of Chapter 3). Maize, durum wheat and sunflower seeds are the main crops cultivated in the region. 2006-2015 is taken as the study period because MAELIA's agricultural and hydrological modules have been calibrated on the case study territory for this study period. Data from this study period produced with MAELIA is duplicated over the 2016-2025 period to characterize WEFN systems over 20 years, which corresponds to the average lifespan of solar panels.

b. Food and electricity territory consumptions

Food and electricity territory consumptions are estimated to derive expert scenarios presented in paragraph d. below. Open data sets are used to calculate the number of inhabitants of the study zone and its mean annual electricity consumption. To evaluate caloric energy and protein consumptions a daily intake of 2.3 kcal and 53.6 grams of proteins per person are considered. The number of inhabitants in the territory is equal to 114805 in 2013 (L'Observatoire des Territoires, 2020). Data from the French energy open data portal (ORE, 2021) is used to calculate the 2015 territory's electricity consumption. Table 1 summarizes caloric, protein and electricity consumption in reference 2013 and 2015 years respectively.

Table 1: Territory's caloric, protein and electricity consumption in reference 2013 and 2015 years respectively

Caloric consumption (2013)	Protein consumption (2013)	Electricity consumption (2015)
9.64E+7 kcal	2.25E+6 kg	7.15E+5 Mwh

e. Examining the utility of the extended version of MAELIA

i. Priority nexus land-allocations to investigate

To determine priority zones to explore, the zone that contains points similar to the 100% Agro regional uniform scenario has been demarcated first. To do this, a ternary diagram has been drawn for each of the ten performance indicators introduced at the end of chapter 2. For each ternary diagram, points that fall into the performance indicator quartile that contains the 100% Agro uniform regional scenario have been coloured in blue. Blue points correspond to scenarios that are most similar to the 100% Agro uniform regional scenario with respect to the performance indicator used to colour points in the given ternary diagram. Appendix A shows the ten ternary diagrams drawn with sample points of WEFN land-use allocation scenarios. Blue points in figures shown in Appendix A cover approximately the same zone for all performance indicators. This is also true for the other three colours used to label points. Since the extended version of MAELIA has been specifically designed to link energy and food resources through the water link, blue zones demarcated in the ternary diagrams of the LWRF [days] and the water indicators are merged and treated as the case study blue zone that contains points similar to the 100% Agro uniform regional scenario. Quartiles of the LWRF [days] indicator are used to demarcate the other three zones that correspond to different levels of performance indicator variations with respect to the reference 100% Agro uniform regional scenario. Quartiles of the LWRF [days] indicator are used to delineate brown, green and purple zones of the case study area because LWRF [days] is a territory indicator used to manage water withdrawals and emit water restrictions that are meaningful and well known by actors of WEFN systems in agricultural watersheds.

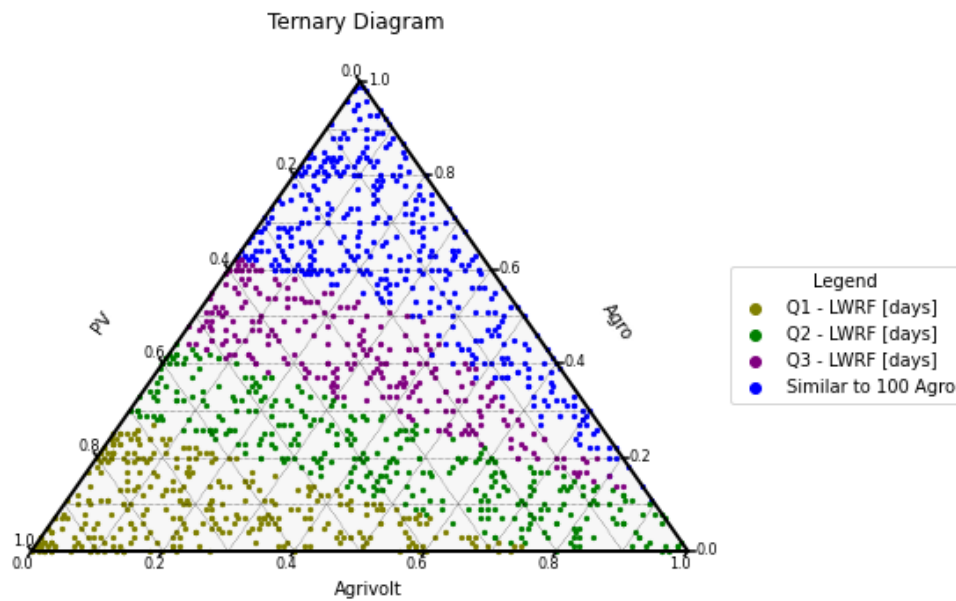


Figure 2: Ternary diagram with blue points delineating the zone that contains points similar to the 100% Agro uniform regional scenario with respect to water related indicators

Red points in figure 3 correspond to scenarios that do not guarantee electricity and food (caloric and protein) autonomies. They are located in the small triangle located to the left down side of the ternary diagram shown in figure 3, with vertices $(0,0,1)$, $(0.2, 0, 0.8)$ and $(0, 0.2, .8)$. This small triangle constitutes the second zone considered not crucial to explore the use of the extended version of Maelia. This zone is closest to the 100% PV uniform regional scenario, which is not a viable scenario for the traditional agricultural watershed territory under study. Red points in this zone do not guarantee the territory's protein autonomy.

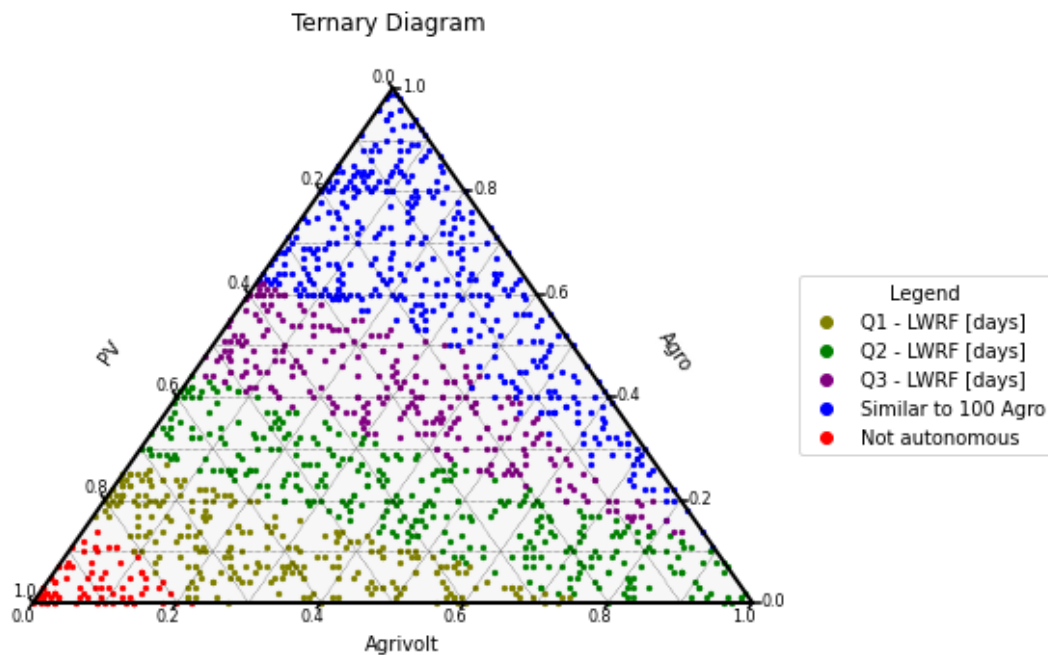


Figure 3: Ternary diagram showing not crucial and priority zones to explore with the extended version of MAELIA

Points coloured in green, brown and purple in figure 3 delimit the zones for which points are simulated with the extended version of MAELIA. The green zone is explored first because it is equally distant from the blue and red zones and therefore constitutes a compromise zone between the two extreme regional uniform 100% Agro and 100% PV scenarios.

ii. *Exploration methodology*

Figure 4 shows a ternary diagram with points for which three scenarios have been simulated with the extended version of MAELIA. The green zone is explored first so points shown in Figure 4 are all in the green zone.

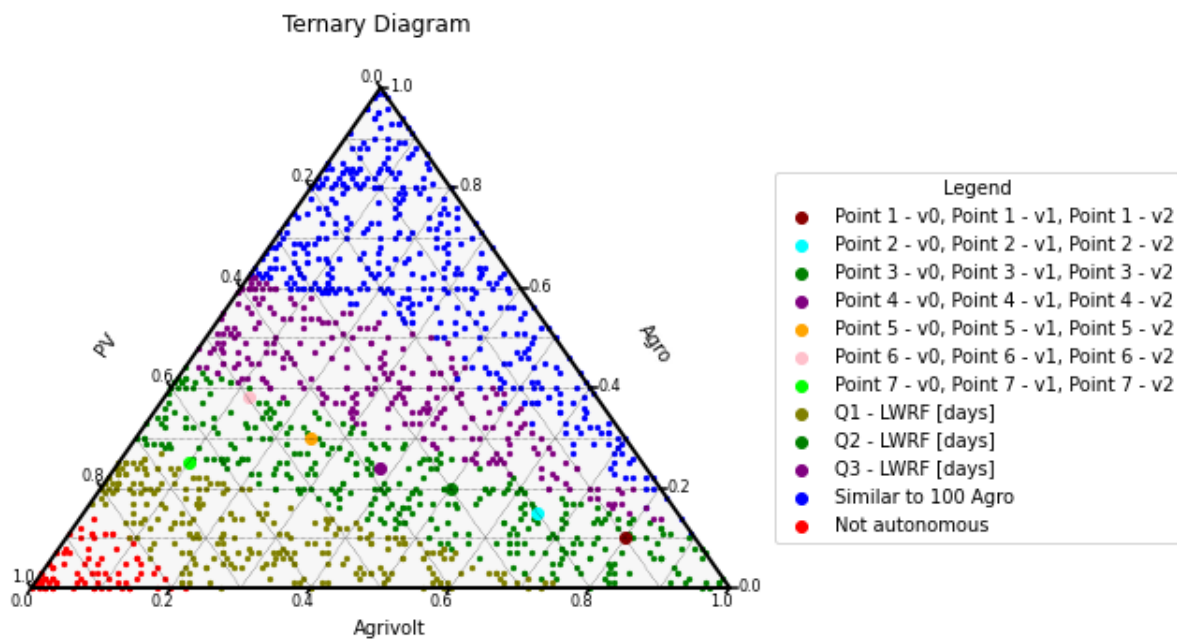


Figure 4: Ternary diagram that shows points for which scenarios have been simulated with the extended version of MAELIA

Table 2 characterizes points simulated with the extended version of MAELIA. It gives percentages of territory parcel entities covered with each land-use alternative for each point. It also indicates values obtained for resources production (Energy agro [J], Energy PV [J], Proteins agro [kg]) and water (Water indicator and LWRF [days]) related indicators. Values shown for each point are means of values obtained from the simulation of three scenarios for each point. Points are ranked in increasing Energy PV [J] order. Values of the two water related indicators vary as expected. From points 1 to 5, mean Water ind and mean LWRF [days] decrease. This is coherent since the total agricultural production decreases as the electricity production from solar panels increases from points 1 to 5. Between point 5 and 6, water related indicators increase, this is due to the simultaneous increase of crops and solar energy productions. From points 1 to 5 the crops energy production decreases as the solar energy production increases. This is due to an increasing number of agricultural parcel entities covered with solar panels from points 1 to 5. From point 5 to 6, the increase of agricultural parcel entities covered with solar panels is less than that between successive points from points 1 to 5, the increase of parcel entities covered with 100% agro land-use alternatives is

higher and the decrease of parcel entities covered with agrivoltaics land-use alternatives is less. Additionally, parcel entities have varying surface sizes. This explains why from points 5 to 6 both agricultural and solar energy production increase. Since the agricultural production is higher for point 6 than for point 5, it is coherent that water related indicators are also higher since more water is needed to produce more crops. From points 6 to 7 the same tendencies are observed as from points 1 to 5.

Table 2: Characterization of the seven points for which three scenarios are simulated with the extended version of MAELIA

	%Agrivolt	%Agro	%PV	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	Water ind	LWRF [days]
Point 1	80	10	10	2,19E+16	8,82E+17	1,55E+08	2,40E+08	872,67
Point 2	65	15	20	2,06E+16	1,02E+18	1,45E+08	2,34E+08	866,00
Point 3	50	20	30	1,90E+16	1,16E+18	1,34E+08	2,10E+08	860,67
Point 4	38	24	38	1,78E+16	1,29E+18	1,25E+08	2,07E+08	857,33
Point 5	25	30	45	1,69E+16	1,37E+18	1,19E+08	1,83E+08	846,00
Point 6	12	38	50	1,71E+16	1,38E+18	1,21E+08	1,96E+08	852,00
Point 7	10	25	65	1,19E+16	1,76E+18	8,36E+07	1,27E+08	816,67

Since variations of water related indicators are coherent between successive points shown in Figure 4 and characterized in Table 2, points have been successively selected in the green zone with cover percentages of land-use alternatives that are 5 to 15% different from point to point.

c. Expert scenarios

Two expert scenarios have been sketched with the objective of defining scenarios that ensure caloric, protein and electricity autonomies for the case study region. A methodology has been developed to design such scenarios for traditional agricultural territories. The objective is set in line with the tendency of moving towards autonomous sustainable local systems. To get parcel-level land-use allocation scenarios that satisfy this objective the methodology starts from the baseline reference agricultural scenario (also named the regional 100% Agro uniform scenario throughout this manuscript). Distinct expert scenarios can be defined with the methodology depending on which solar related land-use alternative it allocates to specific parcels: 100% PV or Agrivoltaics land-use alternatives are considered for our case study region. Figure 5 depicts the methodology. A preliminary step ranks meteorological polygons from the SAFRAN grid (Tribouillois et al., 2022) in increasing crop energy production order based on crop energy productions under the reference agricultural scenario. Data used to design the expert scenarios is issued from simulations run with the extended version of Maelia because it is conceptually more accurate than the standard version, since it simulates water resource state at operational scales. The first step defines an empty list (lists_IDs), to which identifiers of meteorological polygons on which 100% PV or Agrivoltaics alternatives are successively allocated are appended. The second step initializes autonomies variables to keep count of the reached territory electricity and food autonomies. The first iteration allocates solar related land-use alternatives to parcel entities of the first polygon in the ranking established in the preliminary step. Variable lists_IDs and reached autonomies variables are

updated accordingly. If the electricity autonomy is not reached, the methodology launches iteration 2 and sets solar related alternatives to parcel entities of the second polygon in the ranking established in the preliminary step. Once the electricity autonomy is reached, the food autonomy is verified. If the food autonomy is satisfied, an expert scenario that guarantees electricity and food autonomies is defined. If the food autonomy is not satisfied, if it is iteration 0, some parcel entities of the first polygon in list_IDs are allocated back an 100% Agro alternative, otherwise parcel entities of the second to last polygon in list_IDs are allocated back an 100% Agro alternative. Variable lists_IDs and reached autonomies variables are updated accordingly.

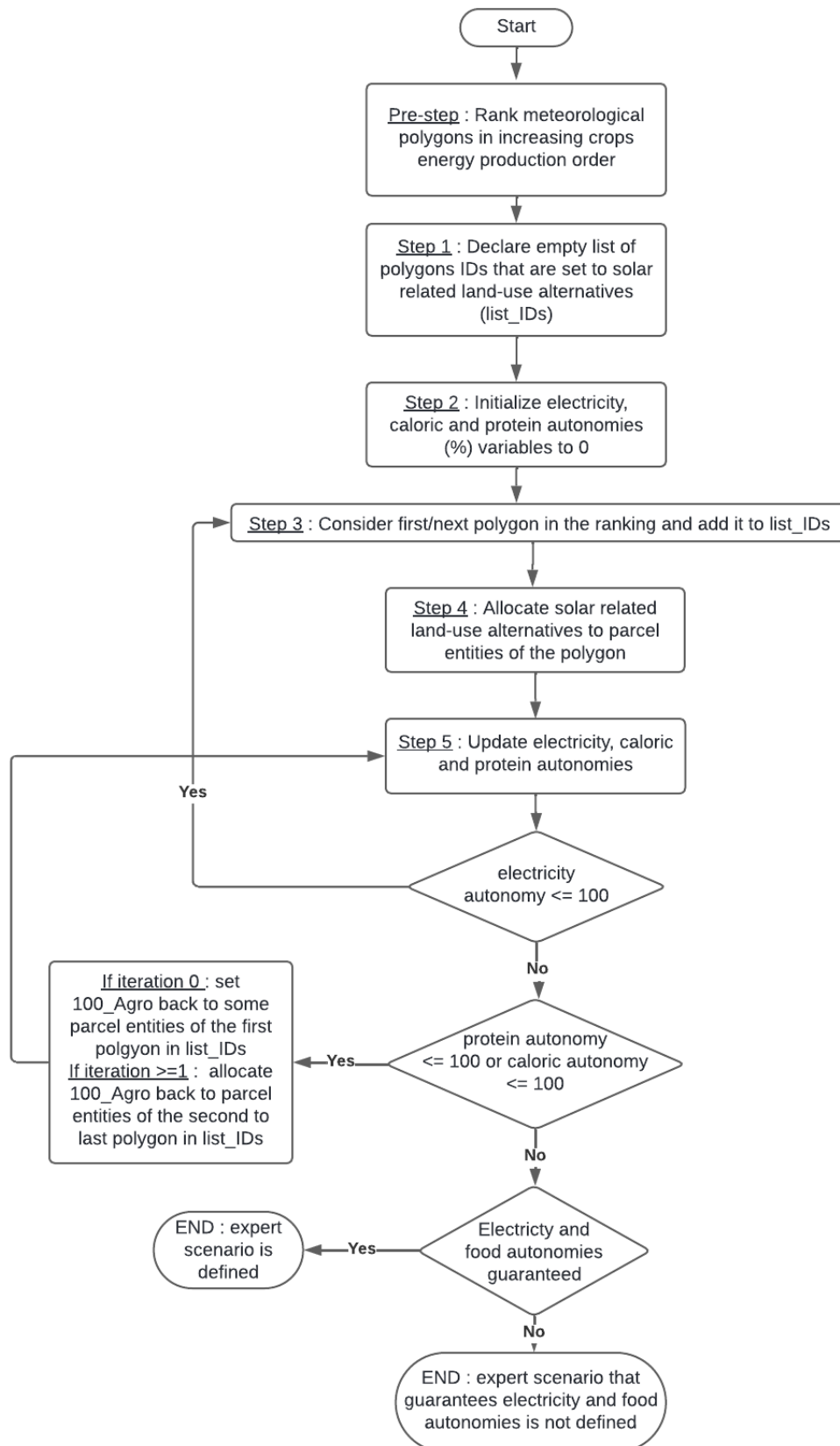


Figure 5: Iterative methodology designed to define expert scenarios for traditional agricultural territories

Expert PV and Agrivoltaics scenarios have been defined with the methodology (cf. fig 5) for the case study territory. The resulting expert scenarios are shown in the results section.

d. The 50-50 parcel and territory scenarios to analyze spatial nexus dependencies

To analyse spatial nexus dependencies with the extended version of Maelia, two scenarios are considered: the 50-50 parcel and territory scenarios. Figure 9 illustrates the 50-50 territory scenario for our case study territory. 8073 parcel entities situated in the northern part are covered with 100% PV land-use alternatives and the 7988 remaining parcel entities are covered with 100% agro land-use alternatives. In total, 195 and 197 km² are covered respectively with solar panels under the 50-50 parcel and 50-50 territory scenarios.

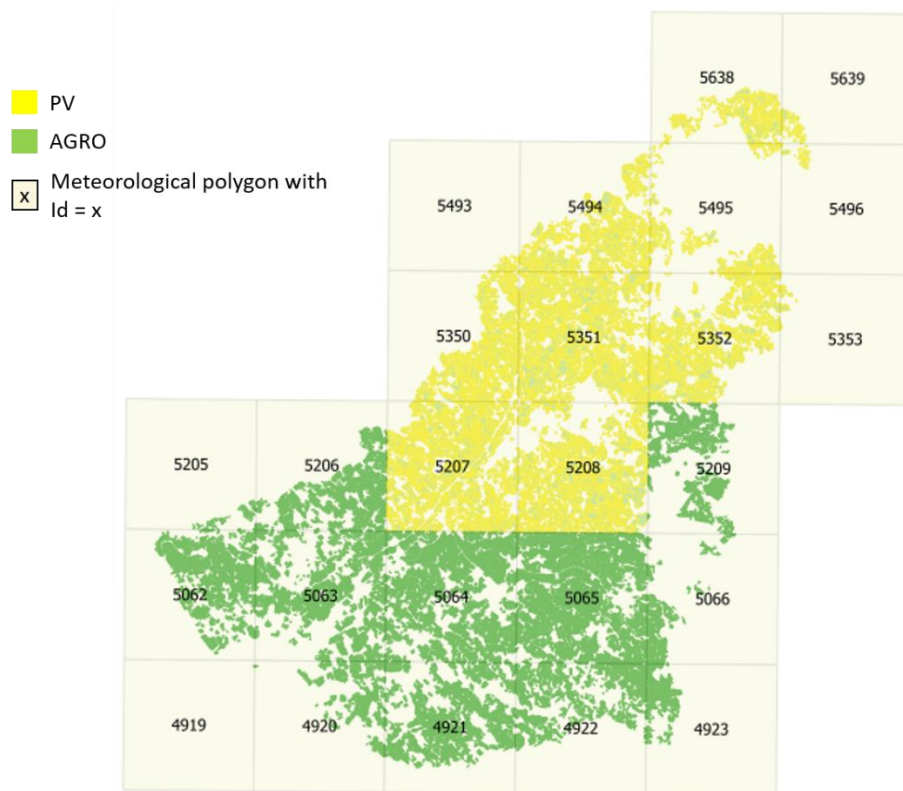


Figure 6: Parcel land-use allocations under the 50-50 territory scenario

IV. Results

a. Scenarios simulated to examine the utility of the extended version of Maelia

i. Three uniform regional scenarios

Table 3 shows performance indicators obtained from the simulation of the two uniform regional scenarios simulated with the extended version of Maelia (also referred to as the new Maelia). Table 9 of chapter 3 shows performance indicators of the three uniform regional scenarios computed from data produced with the standard version of Maelia (also referred to as the old Maelia). Table 4 shows relative changes between indicators computed with the new and old versions of Maelia for the Agrivoltaics and 100% PV uniform regional scenarios. Solar indicator values (Energy PV [J], NPV PV [euros], EF PV [mPts]) are the same because they are not computed based on data produced with Maelia, but on meteorological data external to

Maelia. Table 4 indicates that for both the Agrivoltaics and 100% PV uniform regional scenarios, agricultural energy production indicators (Energy agro [J] and Proteins agro [kg]), the water withdrawal indicator (Water ind) and the social indicator (Farmer labor [h]) are higher when computed with the old Maelia. The territory water related indicator LWRF [days], that represents the total number of days the main river's flowrate goes under a given threshold for a given time period is higher when computed with the new Maelia. For the Agrivoltaics regional uniform scenario, the gross agricultural margin indicator is higher when computed with the old Maelia and the environmental agricultural impact indicator (EF agro [mPts]) is higher when computed with the new Maelia. For the 100% PV regional uniform scenario these two last variations are reversed.

Table 3: WEFN performance indicators from the two uniform regional scenarios simulated with the extended version of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
Agrivolt	2.27E+16	7.74E+17	1.61E+08	7.57E+09	3.03E+08	6.85E+09	8.52E+07	2.40E+08	888	4.89E+05
100 PV	2.11E+11	2.58E+18	1.59E+03	2.53E+10	1.57E+06	2.28E+10	1.08E+04	3.89E+03	764	1.47E+03

Table 4: Relative change between indicators computed with the new and old version of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
Agrivolt	-0.18	0.00	-0.17	0.00	-0.01	0.00	0.14	-0.25	1.50	-0.02
100 PV	-1.00	0.00	-1.00	0.00	0.33	0.00	-0.98	-1.00	-	-0.56

ii. Points in the priority zones of the ternary diagram

Twenty-one scenarios corresponding to the seven points labelled in the ternary diagram shown in Figure 4 have been simulated with the extended version of Maelia. Three random land-use allocation scenarios have been simulated for each point. The ten performance indicators established for water-energy-food nexus systems at the end of chapter 2 have been evaluated for these scenarios. Table 5 shows resulting performance indicators values computed from output data of the simulations with the extended version of Maelia. Table 6 shows performance indicator values obtained for the same twenty-one scenarios but computed from performance indicator values of the reference uniform regional agricultural 100% agro scenario simulated with the standard version of Maelia coupled with the use of food and water hypotheses introduced in chapter 3.

Table 5: WEFN performance indicators from scenarios simulated with the extended version of Maelia

Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
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Point 1	2.19E+16	8.82E+17	1.55E+08	8.63E+09	2.87E+08	7.81E+09	7.86E+07	2.40E+08	872.67	4.62E+05
Point 2	2.06E+16	1.02E+18	1.45E+08	9.96E+09	2.62E+08	9.01E+09	7.10E+07	2.34E+08	866.00	4.26E+05
Point 3	1.90E+16	1.16E+18	1.34E+08	1.14E+10	2.39E+08	1.03E+10	6.34E+07	2.10E+08	860.67	3.84E+05
Point 4	1.78E+16	1.29E+18	1.25E+08	1.26E+10	2.21E+08	1.14E+10	5.74E+07	2.07E+08	857.33	3.55E+05
Point 5	1.69E+16	1.37E+18	1.19E+08	1.34E+10	2.07E+08	1.21E+10	5.30E+07	1.83E+08	846.00	3.33E+05
Point 6	1.71E+16	1.38E+18	1.21E+08	1.36E+10	2.02E+08	1.23E+10	5.03E+07	1.96E+08	852.00	3.29E+05
Point 7	1.19E+16	1.76E+18	8.36E+07	1.72E+10	1.38E+08	1.55E+10	3.45E+07	1.27E+08	816.67	2.26E+05

Table 6: WEFN performance indicators from scenarios evaluated with the standard version of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
Point 1	2.61E+16	8.82E+17	1.83E+08	8.63E+09	2.83E+08	7.81E+09	7.04E+07	3.04E+08	377.19	4.72E+05
Point 2	2.42E+16	1.02E+18	1.69E+08	9.96E+09	2.58E+08	9.01E+09	6.45E+07	2.89E+08	370.55	4.35E+05
Point 3	2.19E+16	1.16E+18	1.53E+08	1.14E+10	2.35E+08	1.03E+10	5.87E+07	2.52E+08	363.89	3.92E+05
Point 4	2.02E+16	1.29E+18	1.41E+08	1.26E+10	2.17E+08	1.14E+10	5.41E+07	2.41E+08	358.54	3.62E+05
Point 5	1.86E+16	1.37E+18	1.30E+08	1.34E+10	2.02E+08	1.21E+10	5.10E+07	2.05E+08	368.33	3.40E+05
Point 6	1.84E+16	1.38E+18	1.29E+08	1.36E+10	1.98E+08	1.23E+10	4.94E+07	2.10E+08	396.74	3.35E+05
Point 7	1.30E+16	1.76E+18	9.04E+07	1.72E+10	1.36E+08	1.55E+10	3.39E+07	1.40E+08	268.48	2.32E+05

Tables 5 and 6 show that agricultural energy production indicators (Energy agro [J] and Proteins agro [kg]), gross margin agro [euros], Water ind (water withdrawal indicator) and the social indicator (Farmer labor [h]) are higher when computed with the old Maelia. The agricultural environmental indicator (EF agro [mPts]) and the territory water related indicator LWRF [days] that indicates the total number of days the main river flowrate goes under a given threshold for a given time period are higher when computed with the new Maelia. These tendencies are illustrated in figures 7 to 13.

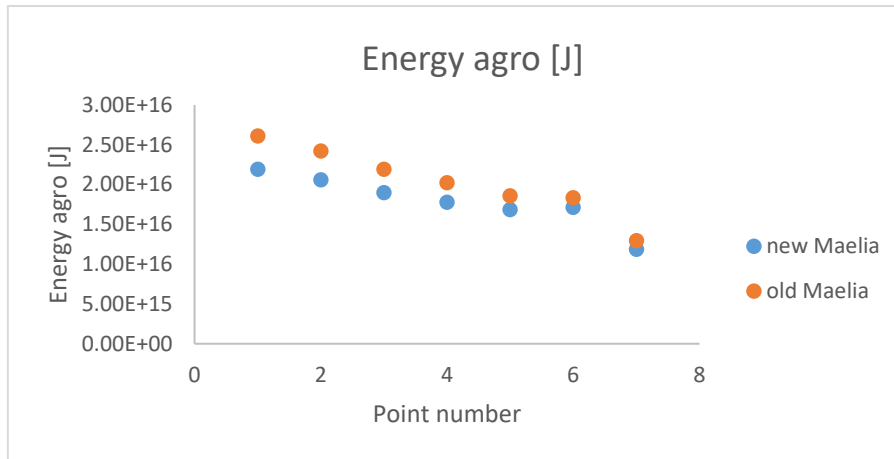


Figure 7: Energy agro [J] for the seven points simulated and characterized with new and old Maelia

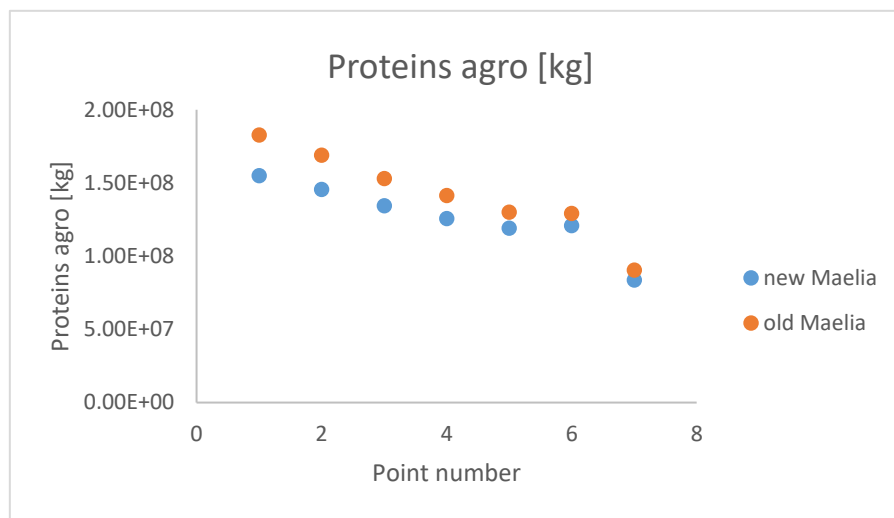


Figure 8: Proteins agro [kg] for the seven points simulated and characterized with new and old Maelia

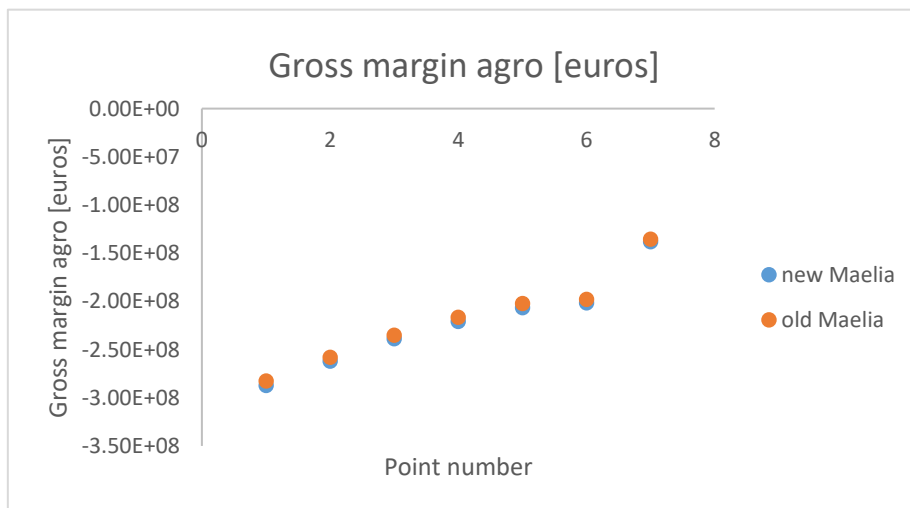


Figure 9: Gross margin agro [euros] for the seven points simulated and characterized with new and old Maelia

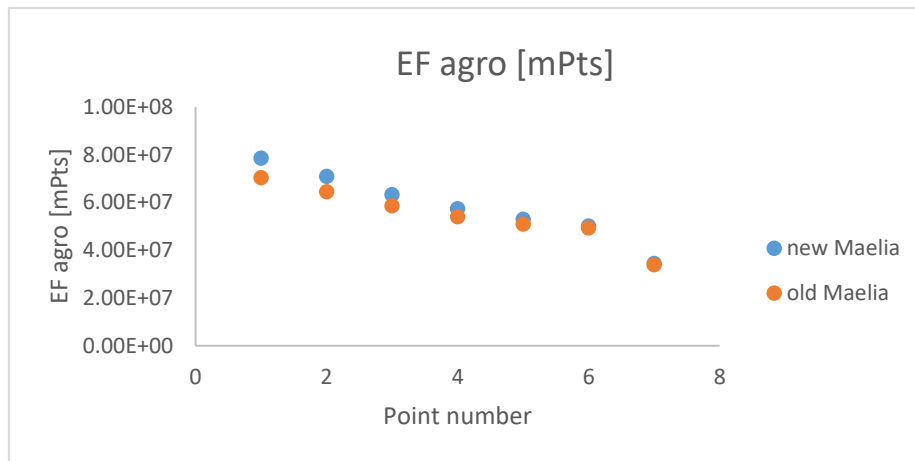


Figure 10: EF agro [mPts] for the seven points simulated and characterized with new and old Maelia

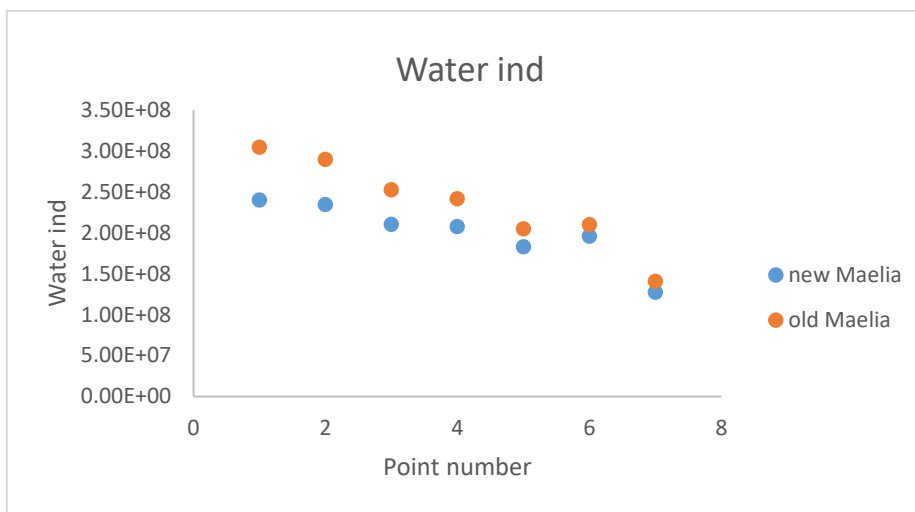


Figure 11: Water ind for the seven points simulated and characterized with new and old Maelia

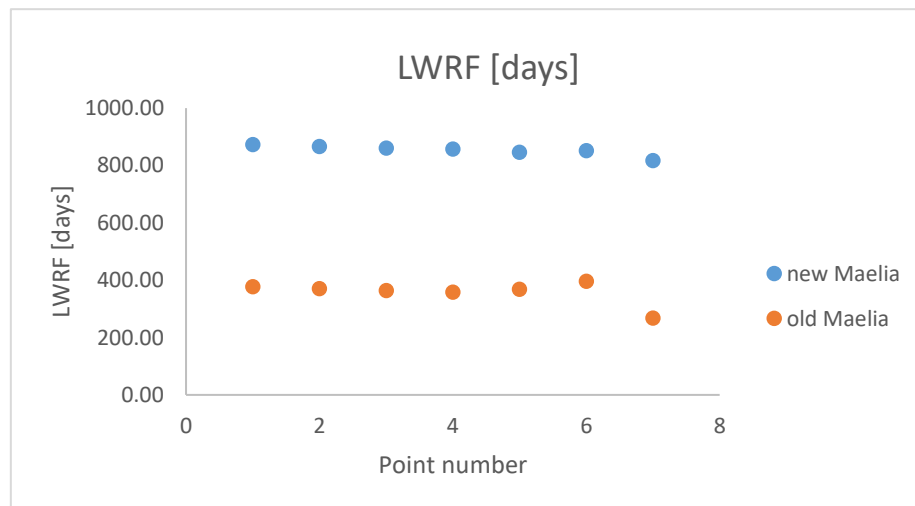


Figure 12: LWRF [days] for the seven points simulated and characterized with new and old Maelia

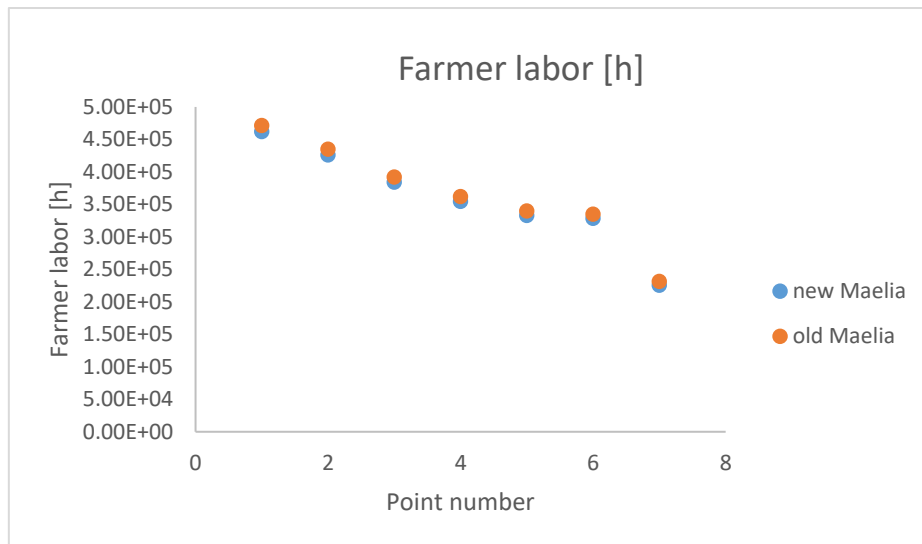


Figure 13: Farmer labor [h] for the seven points simulated and characterized with new and old Maelia

Appendices B and C give performance indicator values obtained for each of the twenty-one scenarios considered. Appendix B shows indicators obtained from output data of simulations with the new Maelia and Appendix C displays indicator values obtained from the use of the old Maelia combined with water and food hypotheses.

b. Expert scenarios built with the extended version of Maelia

This section shares the expert scenarios obtained with the methodology developed for traditional agricultural territories and compares them to the solution scenario obtained with the strategic decision-making methods presented in chapters 3 and 4. Figure 14 illustrates parcel land-use allocations obtained for the expert scenario that allocates 100% PV land-use alternatives to parcels, also named the Expert PV scenario. Parcel entities that are allocated PV land-use alternatives are those in meteorological polygons 4919, 5353, 5638 and 5639. In total, 9.25 km² of agricultural land are covered with solar panels under the expert PV scenario.

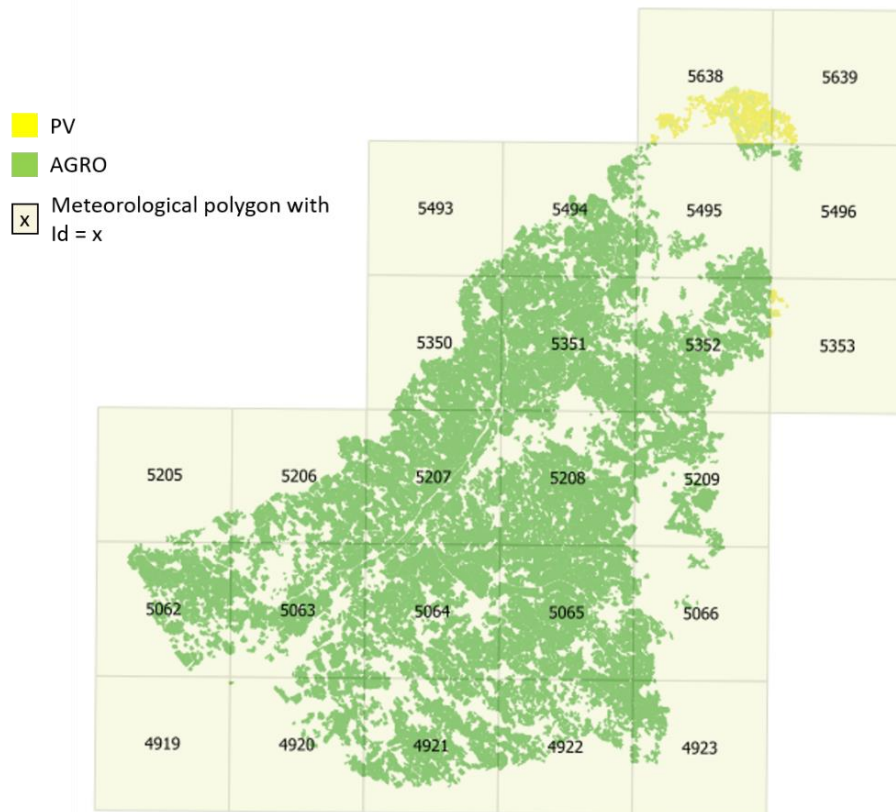


Figure 14: Parcel land-use allocations under the Expert PV scenario

Figure 15 illustrates parcel land-use allocations obtained for the expert scenario that allocates Agrivoltaics land-use alternatives to parcels, also named the Expert Agrivoltaics scenario. Parcel entities that are allocated Agrivoltaics land-use alternatives are those in meteorological polygons 4919, 5353, 5638, 5639, 5495 and 5209. In total, 8.47 km² of agricultural land are covered with solar panels under the expert Agrivoltaics scenario.

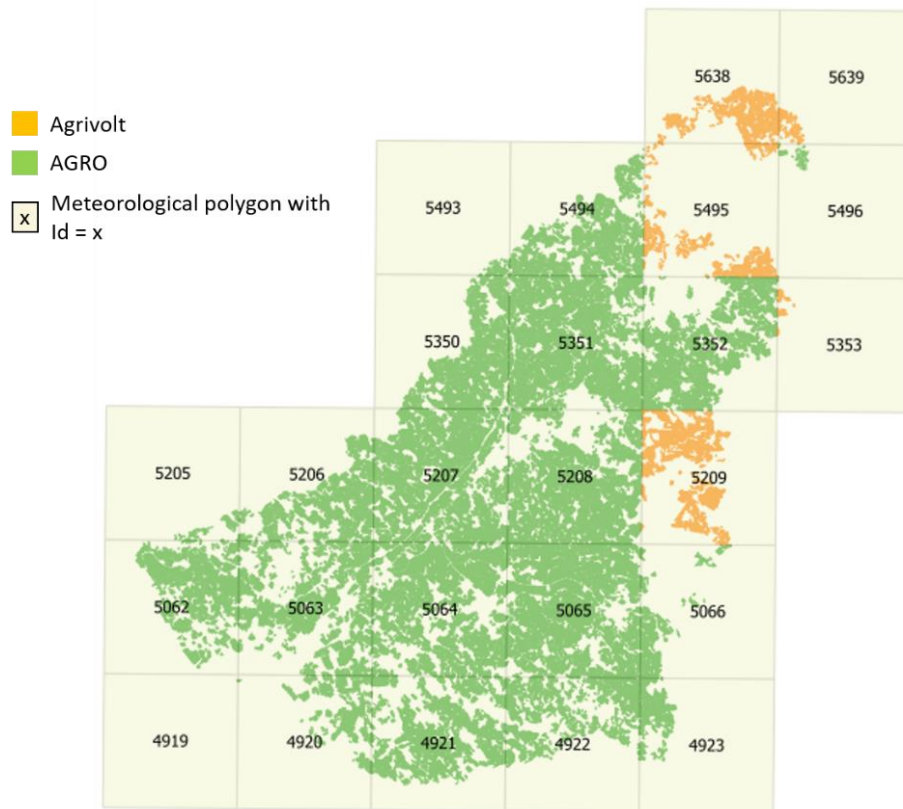


Figure 15: Parcel land-use allocations under the Expert Agrivoltaics scenario

Figure 16 shows the location of the expert scenarios in the ternary diagram used to illustrate the space of possible combinations of parcel land-use allocations for our traditional agricultural territory for which three distinct land-use alternatives can be allocated on each parcel entity: 100% Agro, Agrivoltaics or 100% PV. The point that correspond to the expert PV scenario is shown in yellow and the one that corresponds to the expert Agrivoltaics scenario is shown in red-orange. The solution scenario obtained from applying our multi-level multi-actor framework with the standard Maelia and the multi-criteria and multi-objective strategic decision-making methods presented in chapters 3 and 4 is the 100% PV uniform regional scenario. Figure 16 shows that PV and Agrivoltaics expert scenarios are very different from the solution obtained with our decision-making framework.

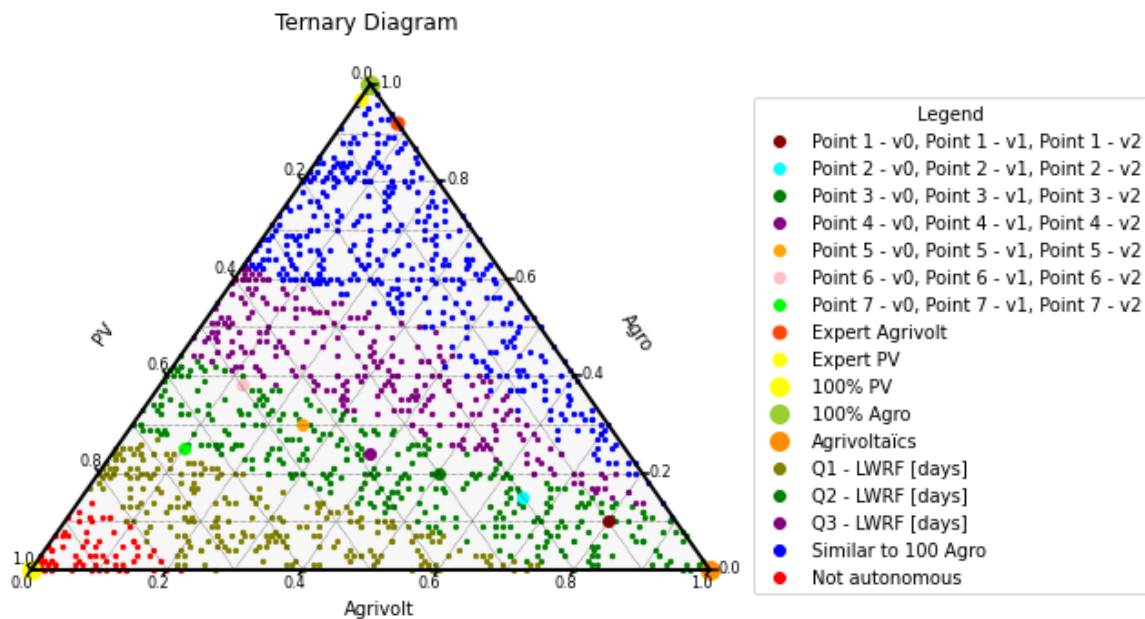


Figure 16: Ternary diagram with priority zones, simulated points and PV and Agrivoltaics expert points

Table 7 shows electricity and food autonomies reached by the two expert scenarios produced for the case study territory and by the 100 PV% uniform regional scenario, which is the solution scenario obtained in previous chapters. Table 7 illustrates that the expert PV scenario guarantees higher electricity and food autonomies than the expert Agrivoltaics scenario, but both scenarios guarantee all three autonomies. The 100% PV uniform regional scenario results in a higher electricity production, it guarantees food caloric autonomy but it does not guarantee food protein autonomy of the traditional agricultural territory.

Table 7: Electricity and food autonomies reached by expert scenarios and the 100% PV uniform regional scenario

	Electricity autonomy (%)	Food caloric autonomy (%)	Food protein autonomy (%)
Expert PV	113	$4 \cdot 10^5$	521
Expert Agrivoltaics	104	$4 \cdot 10^5$	520
100% PV	$5 \cdot 10^3$	$1.63 \cdot 10^3$	2.12

Table 8 displays yields lost under the two expert scenarios examined for the case study territory in tons of crops. It also indicates relative yields lost under the two expert scenarios and under the 100% PV uniform regional scenario with respect to the reference agricultural 100% Agro scenario. Under the two expert scenarios, durum wheat and sunflower seeds are the two main crops for which the number of tones is most reduced with respect to the reference scenario. This is because they are the main crops cultivated in the north-eastern part of the case study territory, where 100% PV and Agrivoltaics land-use alternatives are allocated under the two expert scenarios. Durum wheat, sunflower seeds and soy yields are more reduced under the expert Agrivoltaics scenario than the PV expert scenario. Maize, orchards, pea, rapeseed and grapevine yields are more reduced under the expert PV scenario. Even though maize is the third crop for which the yield in tones is reduced under the expert scenarios, in comparison to the reference agricultural territory maize production, only 1% of

maize yield is lost under the expert PV scenario and 0% percent under the expert Agrivoltaics scenario. Moreover, no maize seeds crops are lost under the expert scenarios. This is because most irrigated maize parcels are located in the middle south part of the case study territory where no parcels are covered with solar related land-use alternatives under the expert scenarios. Crop yields are almost all completely lost under the regional 100% PV scenario.

Table 8: Lost crop yields under expert and the 100% PV uniform regional scenarios with respect to the reference agricultural scenario

	Lost yield (tons) – Expert PV	Lost yield (tons) – Expert Agrivolt	Lost yield (%) – Expert PV	Lost yield (%) – Expert Agrivolt	Lost yield (%) – 100 PV
Durum wheat	2120.54	4491.73	0.23	0.49	99.68
Sunflower seed	112.22	123.12	0.08	0.08	99.64
Maize	42.91	12.87	0.01	0.00	99.07
Orchards	34.03	10.21	0.01	0.00	99.67
Pea	21.62	6.49	0.30	0.09	99.65
Rapeseed	17.09	11.28	0.05	0.03	99.47
Grapevine	7.98	5.14	0.12	0.08	99.80
Soy	0.00	3.38	0	0.01	1.00
Maize seeds	0.00	0.00	0	0	99.70

Expert scenarios have been designed with data produced from simulating regional uniform scenarios with the extended version of Maelia. Since they are located in the ternary diagram zone that contains points most similar to the 100% Agro scenario (see Figure 8), expert scenarios have both been simulated with the extended version of Maelia and characterized with the standard version of Maelia combined with water and food hypotheses to see if and how much the resulting evaluations differ. This enables us to explore the use of the extended version of Maelia for scenarios that are similar to 100% Agro uniform regional scenario. Table 9 shows performance indicators obtained with the extended version of Maelia and table 10 shows indicators obtained from the use of water and food hypotheses combined with the standard version of Maelia. Both tables illustrate that no matter the version of Maelia used, agricultural indicators are almost the same for expert PV and expert Agrivoltaics scenarios. Table 11 shows relative change between indicators computed with the new and old versions of Maelia for the Agrivoltaics and PV expert scenarios. The only indicator which value varies from the use of the extended and standard Maelia is the LWRF [days] indicator. The difference is of 5% for the Agrivoltaics expert scenario and of 3% for the PV expert scenario.

Table 9: WEFN performance indicators of expert scenarios simulated with the extended version of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
Expert Agrivolt	3.95E+16	5.40E+16	2.76E+08	5.23E+08	4.27E+08	4.96E+08	1.06E+08	4.55E+08	934	7.12E+05
Expert PV	3.96E+16	5.81E+16	2.76E+08	5.61E+08	4.27E+08	5.42E+08	1.06E+08	4.55E+08	932	7.12E+05

Table 10: WEFN performance indicators of expert scenarios computed with water and food hypotheses

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
Expert Agrivolt	3.96E+16	5.40E+16	2.76E+08	5.23E+08	4.26E+08	4.96E+08	1.06E+08	4.55E+08	886.73	7.12E+05
Expert PV	3.96E+16	5.81E+16	2.76E+08	5.61E+08	4.26E+08	5.42E+08	1.06E+08	4.55E+08	907.11	7.12E+05

Table 11: Relative change between indicators of the expert scenarios computed with the new and old versions of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
Expert Agrivolt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
Expert PV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00

c. 50 - 50 parcel and territory scenarios

Table 12 recapitulates WEFN performance indicators obtained from simulations with the extended version of Maelia for both 50-50 parcel and territory scenarios that cover 50% of the territory with solar panels and relative ratios of indicators obtained for the territory scenario to those obtained with the parcel scenario. The last row of the table portrays that all WEFN indicators obtained for the 50-50 territory scenario are bigger in absolute values than those obtained for the 50-50 parcel scenario, except from the social indicator (Farmer labor [h]).

Table 12: WEFN performance indicators of 50 – 50 scenarios simulated with the extended version of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
50-50 parcel	1.03E+16	1.29E+18	7.70E+07	1.26E+10	2.13E+08	1.14E+10	5.00E+07	1.20E+08	848	3.39E+05
50-50 territory	2.36E+16	1.29E+18	1.55E+08	1.26E+10	2.67E+08	1.16E+10	6.71E+07	3.49E+08	888	3.05E+03
Territory/Parcel	2.29	1.00	2.01	1.00	1.26	1.01	1.34	2.91	1.05	0.01

Figure 17 shows that the 50-50 territory scenario is situated in the purple zone of the ternary diagram that illustrates the space of possible combinations of parcel 100% PV, Agrivoltaics and 100% agro land-use alternatives allocations combinations for our case study territory. This zone has not yet been explored methodically because of limited time available. We have therefore also characterized the 50-50 territory scenario and the 50-50 parcel scenario with the use of water and food hypotheses combined with the standard version of Maelia to broaden our analysis of the extended version of Maelia. Table 13 shows performance

indicators obtained for the 50-50 scenarios with the standard version of Maelia and table 14 gives relative changes obtained for indicators of the 50-50 scenarios computed with the new version of Maelia with respect to those obtained with the standard version of Maelia. Table 14 exposes that LWRF [days] is always higher when computed with the new version of Maelia for the two 50-50 scenarios. For the 50-50 territory scenario, all indicators are higher when computed with the new version of Maelia except from the water withdrawal indicator, which is slightly smaller and the social indicator, which is considerably smaller. For the 50-50 parcel scenario, except for the LWRF [days] indicator, all indicators are smaller when computed with the new version of Maelia.

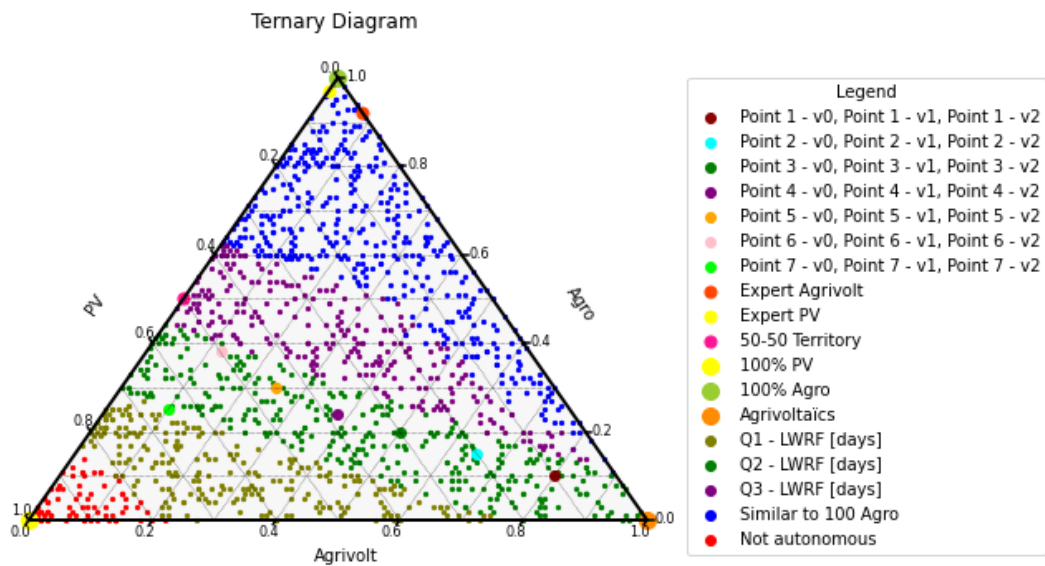


Figure 17: Ternary diagram that shows where the 50-50 territory scenario is located with respect to other points explored

Table 13: WEFN performance indicators of 50 – 50 scenarios characterized with the standard version of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
50-50 parcel	1.99E+16	1.29E+18	1.39E+08	1.26E+10	2.14E+08	1.14E+10	5.34E+07	2.30E+08	82	3.58E+05
50-50 territory	1.59E+16	1.29E+18	1.16E+08	1.26E+10	2.68E+08	1.16E+10	6.73E+07	3.52E+08	72	3.94E+05

Table 14: Relative change between indicators of 50-50 scenarios computed with the new and old versions of Maelia

	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
50-50 parcel	-0.48	0.00	-0.45	0.00	-0.01	0.00	-0.06	-0.48	9.34	-0.05
50-50 territory	0.48	0.00	0.33	0.00	0.00	0.00	0.00	-0.01	11.33	-0.99

d. Computational performances

Table 15 summarizes computational times of operational simulations of nexus systems and of performance indicators processing steps with the new and old versions of Maelia. The duration of the simulation of the uniform regional 100% Agro scenario run with the extended version of Maelia and the standard version of Maelia is equal since when the 100% Agro scenario is run with the extended version of Maelia input variables defined specifically to simulate renewable energy generation units in agricultural land are set to 0. Operational simulation times of WEFN systems with the new version of Maelia last from 18 hours 54 minutes (duration for the regional 100% PV scenario) up to 5 days 3 hours 39 minutes (duration for point 1 -v0, which refers to the first random scenario that corresponds to land-use allocation distributions of point 1 drawn in Figure 4). The performance indicator processing workflow designed to treat output data from the new Maelia lasts from 6 minutes (duration for the regional 100% PV scenario) to 31 minutes (duration for the expert PV scenario). The performance indicator processing workflow implemented with the old Maelia lasts less than 1 second for all points drawn in Figure 4 and for expert scenarios and less than 1 minute for 50-50 scenarios. However these workflows require the reference 100% Agro scenario to have been simulated with Maelia and performance indicator processing workflows of regional uniform scenarios corresponding to land-use allocation types they allocate to parcels to have been run.

Table 15: Computational times with the extended (new) and the standard (old) versions of Maelia

	New Maelia - Operational simulation (time)	New Maelia - Performance indicator processing (time)	Old Maelia - Performance indicator processing (time)
Regional 100% Agro	31 hours 22 minutes	24 minutes	24 minutes
Regional Agrivoltaics	31 hours 54 minutes	20 minutes	< 1 minutes
Regional 100% PV	18 hours 54 minutes	6 minutes	17 minutes
Point 1 - v0	5 days 3 hours 39 minutes	21 minutes	< 1 sec
Point 1 - v1	35 hours 17 minutes	24 minutes	< 1 sec
Point 1 - v2	31 hours 20 minutes	21 minutes	< 1 sec
Point 2 - v0	4 days	24 minutes	< 1 sec
Point 2 - v1	30 hours 13 minutes	20 minutes	< 1 sec
Point 2 - v2	30 hours 24 minutes	25 minutes	< 1 sec
Point 3 - v0	32 hours 18 minutes	24 minutes	< 1 sec
Point 3 - v1	2 days 19 hours 12 minutes	23 minutes	< 1 sec
Point 3 - v2	27 hours 53 minutes	20 minutes	< 1 sec
Point 4 - v0	26 hours 35 minutes	19 minutes	< 1 sec
Point 4 - v1	27 hours 24 minutes	15 minutes	< 1 sec
Point 4 - v2	26 hours 9 minutes	22 minutes	< 1 sec
Point 5 - v0	25 hours 37 minutes	17 minutes	< 1 sec
Point 5 - v1	43 hours 31 minutes	15 minutes	< 1 sec
Point 5 - v2	24 hours 50 minutes	16 minutes	< 1 sec

Point 6 - v0	25 hours 6 minutes	17 minutes	< 1 sec
Point 6 - v1	2 days 4 hours 18 minutes	15 minutes	< 1 sec
Point 6 - v2	33 hours	19 minutes	< 1 sec
Point 7 - v0	3 days 19 hours 41 minutes	14 minutes	< 1 sec
Point 7 - v1	22 hours 35 minutes	12 minutes	< 1 sec
Point 7 - v2	22 hours 24 minutes	15 minutes	< 1 sec
Expert PV	31 hours 54 minutes	31 minutes	< 1 sec
Expert Agrivoltaïcs	32 hours 53 minutes	25 minutes	< 1 sec
50-50 parcel	31 hours 24 minutes	23 minutes	< 1 minutes
50-50 territory	27 hours	16 minutes	< 1 minutes

V. Discussion

a. Scenarios simulated with the extended version of Maelia

Simulating the 100% PV and Agrivoltaïcs uniform regional scenarios with the extended version of Maelia and comparing the resulting WEFN performance indicators with those obtained from the use of the standard Maelia has illustrated that the use of the standard Maelia coupled with water and food hypotheses led to overestimating agricultural caloric and protein yields at territory level. It also resulted in overestimating the water indicator and the state of the territory water resource characterized by the LWRF [days] indicator. The overestimation of the water indicator is proportional to the overestimation of the crop yields. LWRF [days] computed with the new Maelia is one times and a half higher for the regional Agrivoltaïcs scenario and goes from zero to 764 days for the 100% PV uniform regional scenario. The magnitude of the variation of this indicator is not surprising since water hypotheses used to compute it from outputs of the standard version of Maelia were oversimplifying. The regional value of the LWRF [days] indicator under the three regional uniform scenarios considered was treated as a constant parcel level indicator and a territory spatial mean was computed to obtain a regional indicator value for non-uniform regional scenarios that result from combinations of 100% PV, 100% Agro and Agrivoltaïcs parcel level land-use allocations. The extended version of Maelia simulates the fact that water that is evapotranspired in a plot under the reference agricultural scenario flows back into the water resource if a solar panel is installed on that plot. It therefore simulates water resource dynamics at operational parcel level and the LWRF [days] indicator evaluates and characterizes the resulting state of the water resource at territory level. The social indicator is also overestimated with the old version of Maelia coupled to water and food hypotheses. For the uniform 100% PV scenario, its overestimation is however less than that of crop caloric and protein yields. This is explained by the fact that water and food hypotheses used to compute WEFN indicators from outputs of the standard version of Maelia assumed linear dependencies, which does not match real life since the number of hours worked by farmers is not linearly proportional to the cultivated plot surface. For the gross agricultural margin and the environmental agricultural impact indicator, the variations are less clear since the tendencies are reversed between the

Agrivoltaics and 100% PV regional uniform scenarios. For the Agrivoltaics scenario, small variations (less than 0.14 of relative change) are observed. The gross agricultural margin is smaller and the environmental agricultural impact indicator is higher when computed from outputs of the extended version of Maelia. The reason behind the agricultural gross margin being slightly smaller is due to the hypothesis according to which southern crop yields are increased with the extended version of Maelia, because more water is available for southern parcels when solar panels are installed in northern parcels. The increase of southern crop yields does not however compensate the decrease of total territory crop yields. Since operating costs are constant because total agricultural surfaces are the same with the standard and extended versions of Maelia for the same scenario, the gross agricultural margin obtained with the extended version of Maelia is thus lower. The increase in environmental impact can be due to the hypothesis according to which crop yields of parcels situated in the southern part of the territory are higher with the new Maelia. Since southern crop yields are higher with the new Maelia and since crops situated in the southern part of our case study territory have higher environmental impact scores than those situated in the northern part, the territory environmental impact score is slightly higher with the new Maelia. These tendencies are reversed under the 100% PV regional uniform scenario because the total territory surface covered with solar panels is smaller under the Agrivoltaics uniform regional scenario than under the 100% PV uniform regional scenario. Consequently, the effects of the total crop energetic and protein yields reduction observed with the extended version of Maelia is more noticeable for the 100% PV uniform regional scenario than for the Agrivoltaics PV uniform regional scenario. The impact of the territory total reduction of crop caloric and protein yields prevails and takes the lead over the increase of southern crop resulting in variations that range from 0.33 for the gross agricultural margin to -0.98 for the agricultural environmental impact score for the 100% PV scenario. The underestimation of the gross agricultural margin with the old Maelia goes along the overestimation of crop yields since for our case study scenario no agricultural governmental subsidies are considered so higher crop yields lead to lower agricultural gross margins. Obtaining a lower agricultural environmental impact with the new Maelia for the 100% PV scenario is also coherent with obtaining smaller agricultural yields since apart from meadows, which do not represent the major crops in the study zone, higher crop yields correspond to higher agricultural environmental impacts.

Figures 7 to 13 corroborate common tendencies observed for the Agrivoltaics and 100% PV regional uniform scenarios. Crop protein and caloric yields are overestimated with the standard version of Maelia for WEFN scenarios that allocate solar panels related land-use alternatives in agricultural land. Table 16 shows that the overestimation ranges from 16% to 7% for points situated in the green zone of the ternary diagram shown in Figure 4, which is a compromise zone between the 100% Agro and the 100% PV regional uniform scenarios. The water withdrawal indicator is overestimated by 21% to 9% with the standard version of Maelia. The social indicator is overestimated by 2% to 3% with the standard version of Maelia. LWRF [days] indicator is significantly underestimated with the standard of Maelia. The LWRF

[days] indicator obtained with the new Maelia is up to the double of that derived from the standard Maelia. The tendencies of the gross agricultural margin and of the environmental impact indicator match that of the Agrivoltaics regional uniform scenario. The gross agricultural margin is overestimated with the standard version of Maelia by 2%. The environmental impact indicator is underestimated by 12% to 2% with the standard version of Maelia.

Table 16: Relative change between indicators of the 7 ternary diagram points derived from the new and old versions of Maelia

	Energy agro [J]	Energy PV [J]	Protein s agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
Point 1	-0.16	0.00	-0.15	0.00	-0.02	0.00	0.12	-0.21	1.31	-0.02
Point 2	-0.15	0.00	-0.14	0.00	-0.02	0.00	0.10	-0.19	1.34	-0.02
Point 3	-0.13	0.00	-0.12	0.00	-0.02	0.00	0.08	-0.17	1.37	-0.02
Point 4	-0.12	0.00	-0.11	0.00	-0.02	0.00	0.06	-0.14	1.39	-0.02
Point 5	-0.09	0.00	-0.08	0.00	-0.02	0.00	0.04	-0.11	1.30	-0.02
Point 6	-0.07	0.00	-0.06	0.00	-0.02	0.00	0.02	-0.07	1.15	-0.02
Point 7	-0.08	0.00	-0.08	0.00	-0.02	0.00	0.02	-0.09	2.04	-0.03

The main highlight from this section is that the standard version of Maelia coupled to water and food hypotheses strongly underestimate the value of the territory water indicator LWRF [days]. The underestimation is up to 50% for points situated in the green zone of the ternary diagram shown in Figure 4. This section has also shown that variations of performance indicators computed with the two distinct versions of Maelia are similar for the regional uniform Agrivoltaics scenario and for points in the green zone shown in Figure 4. The green zone is a compromise zone between 100% Agro and 100% PV regional uniform scenarios and is does not surprising that performance indicators of points in the green zone vary in the same way performance indicators of the Agrivoltaics uniform regional do.

b. Expert scenarios built with the extended version of Maelia

The two expert scenarios result in solar panels covering less than 10 km² of the 391 km² agricultural surface of the case study territory under the reference agricultural scenario. The evaluation of the expert scenarios from outputs of simulations run with the extended version of Maelia and from outputs of simulations of the reference agricultural scenario run with the standard version of Maelia combined with water and food hypotheses has shown that only the resulting value of the LWRF [days] indicator differs between the two evaluations. The relative change is of 5% for the Expert Agrivoltaics scenario and of 3% for the Expert PV scenario. The relative change being higher for the Expert Agrivoltaics scenario is intrinsically linked to the hypothesis applied to compute the LWRF [days] from outputs of the simulation of the reference agricultural scenario with the standard version of Maelia. Since the number of parcels covered with the Agrivoltaics land-use alternative is higher under the Expert Agrivoltaics scenario than the number of parcels covered with the 100% PV land-use alternative under the Expert PV scenario, the linear hypothesis that calculates the total ETP

that flows back to the main watercourse is applied a bigger number of times. Consequently, this can result in a bigger overestimation of the quantity of water that is assumed to flow back to the main territory watercourse for the Expert Agrivoltaics scenario.

Figure 18 shows a spider graph of the performance indicators obtained for the expert scenarios vs those obtained for the solution of the multi-actor multi-level framework (100 PV) simulated with the extended version of Maelia. For simplicity issues, since all indicators obtained for the two distinct (PV and Agrivoltaics) expert scenarios are the same except for LWRF [days], which is slightly different (less than 1% different), indicators of the expert PV scenario are kept as the indicators of both expert scenarios. The spider graph in Figure 18 conveys that expert scenarios benefit more the agricultural sector but are more water intensive than the solution obtained with our multi-level multi-actor framework that combines the standard Maelia, with a multi-criteria strategic decision-making method in chapter 3 and with a multi-objective optimization method in chapter 4. The 100 PV scenario obtained with our multi-level level multi-actor decision-making framework in previous chapters benefits more solar production indicators and has a less negative impact on the water resource (smaller LWRF [days] and water withdrawal indicator). A smaller water withdrawal indicator also leads to less potential social water conflicts caused by multi-sector actors fighting to access limited water resources. However, the environmental life cycle footprint of the 100 PV scenario is higher than that of the expert scenarios. Moreover, expert scenarios guarantee all electricity, food caloric and protein autonomies, whereas the 100 PV scenario does not guarantee the territory protein autonomy (cf. Table 7). Note that simulating the 100 PV scenario with the extended Maelia leads to a smaller decrease of LWRF [days] of the 100 PV scenario with respect to that of the expert scenarios. Simulating the nexus systems completely at operational scale has enabled a more precise assessment of water resource state, which is intrinsically linked to land-use agricultural and energy competitions. Figure 18 illustrates multi-actor and multi-sector trade-offs between expert scenarios and the 100% PV scenario obtained with our multi-level multi-actor framework that relies on operational simulations of nexus systems run with the standard Maelia.

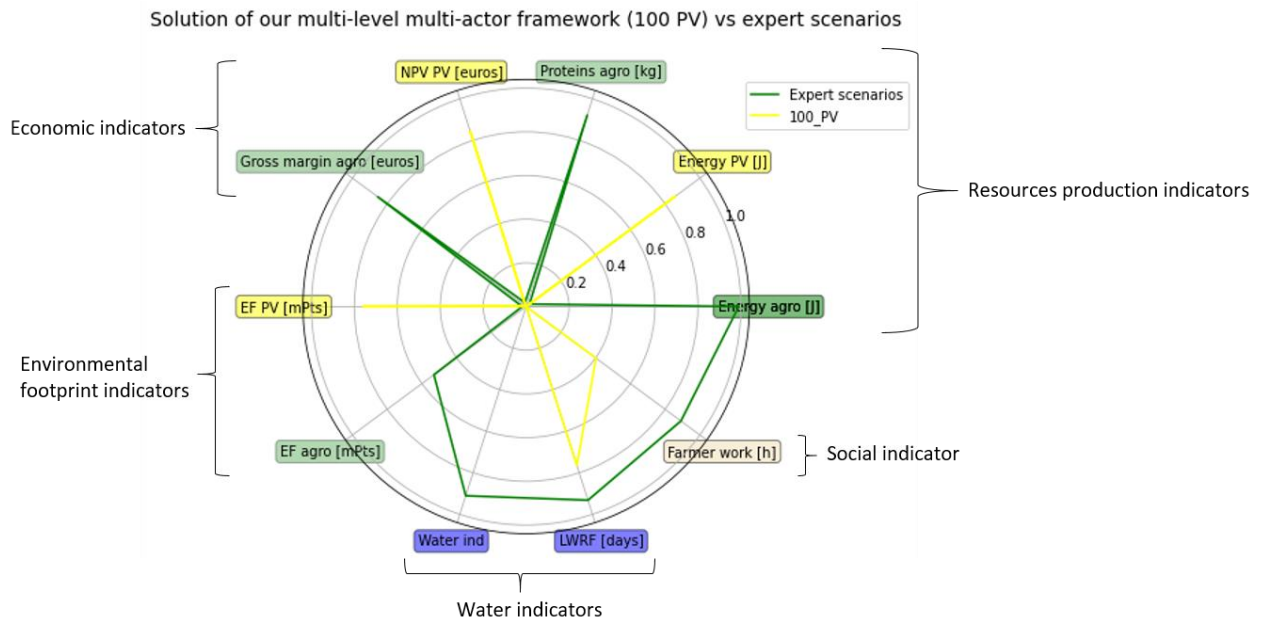


Figure 18: Spider graph of multi-sector WEFN performance indicators of the solution of the multi-actor multi-level framework (100 PV) vs that of the expert scenarios

c. Analysing spatial nexus dependencies with the two 50-50 scenarios

The simulations and evaluations of the two 50-50 scenarios, which cover 50% of the territory's agricultural land with solar panels in two different ways, with the extended version of Maelia have shown that all indicators, except from the social farmer labor [h] indicator, are bigger in absolute values for the 50-50 territory scenario than for the 50-50 parcel scenario. This is partly due to the southern part of the territory accounting with higher agricultural potentials under the reference agricultural scenario as conveyed by Figures 19 and 20.

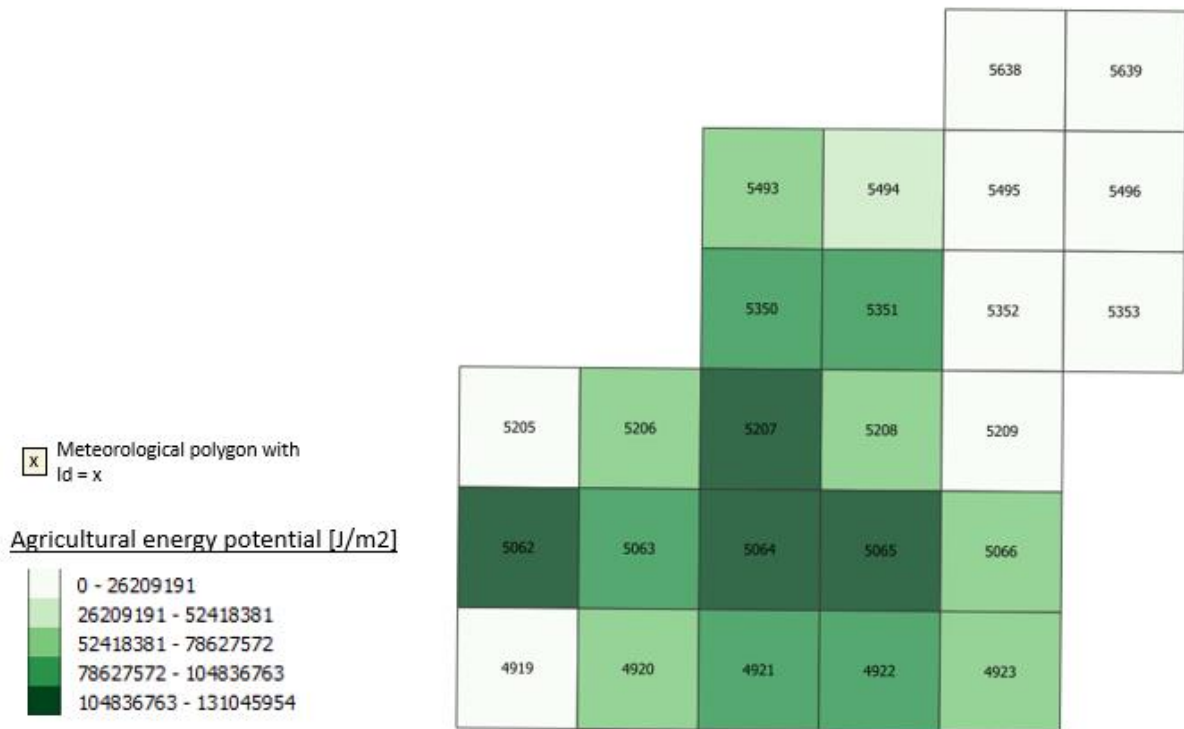


Figure 19: Agricultural energy potentials of the 25 meteorological polygons of the case study territory

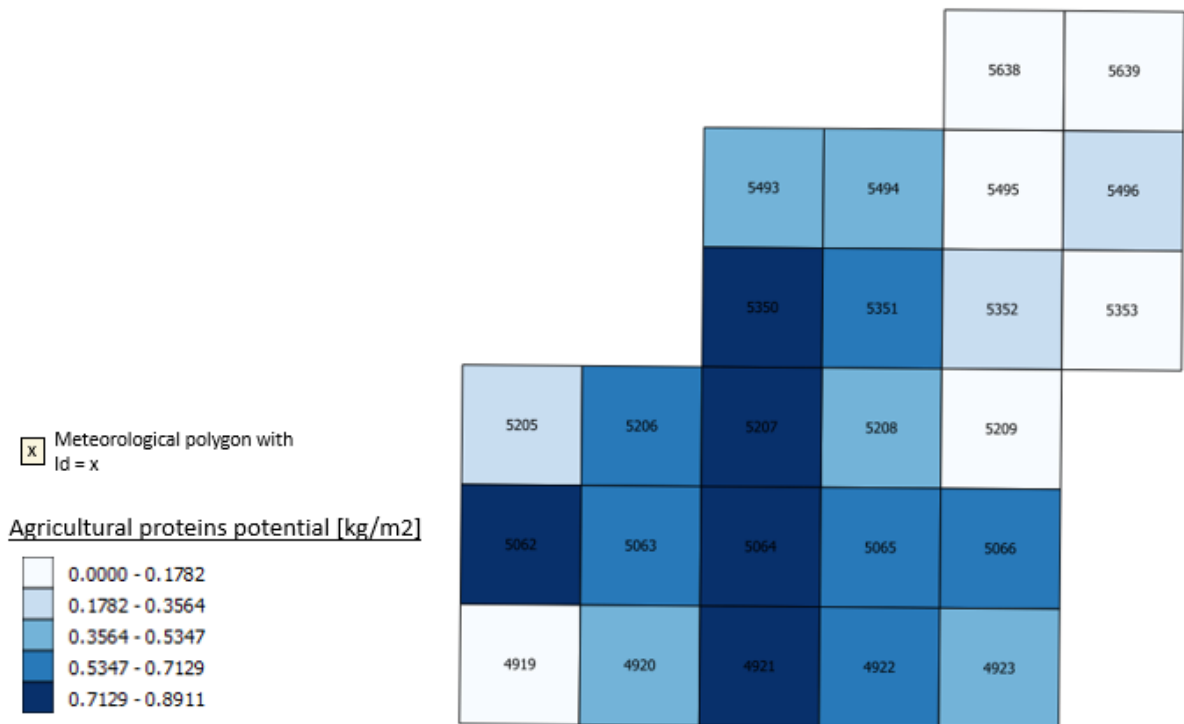


Figure 20: Agricultural proteins potentials of the 25 meteorological polygons of the case study territory

The comparison of the characterization of both scenarios with the extended and standard versions of Maelia has shown that agricultural production (energy and proteins) indicators were underestimated for the 50-50 territory with the standard version of Maelia. Considering that up until now for all scenarios simulated with both versions of Maelia the crop yields were always overestimated with the standard version of Maelia, this corroborates the hypothesis

that states that installing solar panels in the northern part of the territory results in more water being available for plots situated in the southern part of the territory. Therefore, plots in the southern part of the territory account with bettered agricultural yields. The fact that even though crop yields are underestimated by the standard version of Maelia, the water withdrawal indicator is overestimated goes along the previous hypothesis. Since the extended version of Maelia proves that installing solar panels in the northern part of the territory results in higher crop yields than expected without implying higher water withdrawals rates. Relative changes observed for the 50-50 parcel scenario validate the tendencies observed for the points simulated with the extended version of Maelia and situated in the green zone of Figure 4, except for the variation of the EF agro [mPts] indicator which is 6% smaller when computed with the extended version of Maelia for the 50-50 parcel scenario. The EF agro [mPts] variation is coherent since the reduction in crop yields for the 50-50 parcel scenario computed with the new Maelia in comparison to those computed with the old Maelia is higher than that observed for points situated in the green zone of Figure 4 (see Tables 14 and 16).

The analysis of the results obtained from the simulations of both 50-50 scenarios has shown that from a resources production point of view covering the northern half of the territory with solar panels is more profitable for agricultural yields than covering half of each parcel of the whole territory with solar panels. However, the 50-50 territory solution is also worst from an environmental and economic point of view and would cause inequalities between farmers since farmers situated in the northern part would lose their jobs. Figure 21 illustrates these tendencies and highlights the resulting trade-offs. The highlight of this section is that the location of solar panels at operational levels affects territory strategic performance indicators.

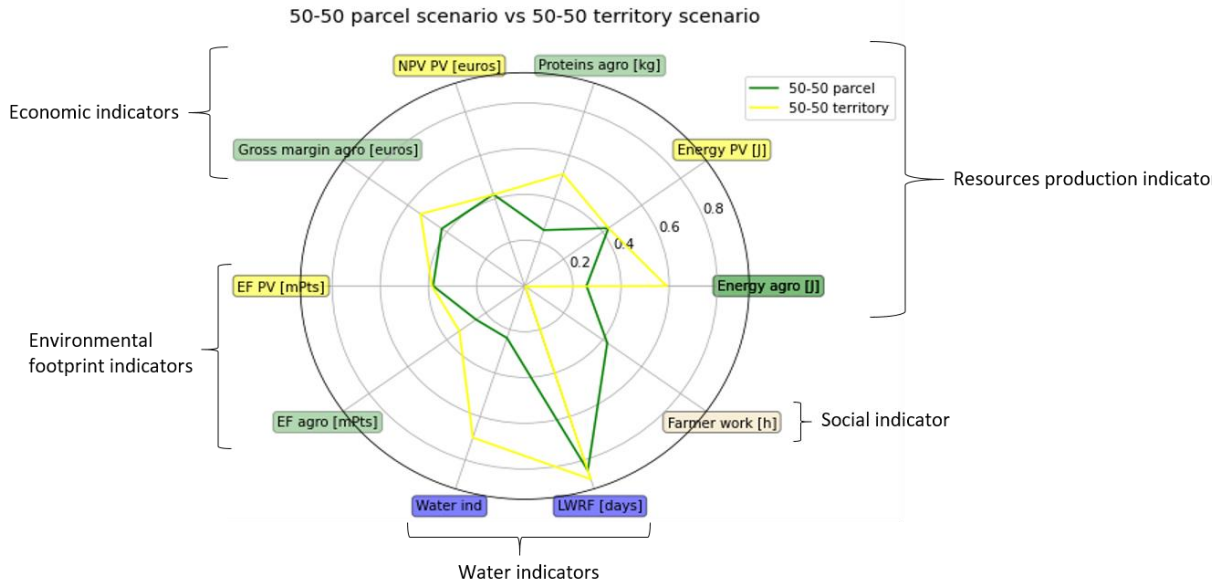


Figure 21: Spider graph of multi-sector WEFN performance indicators of the two 50-50 scenarios

d. Simulating complete WEFN systems at operational scales

Analysis of the uniform regional scenarios, the seven points situated in the green zone of the ternary diagram shown in Figure 4, the expert scenarios and the 50-50 scenarios have shown that non-negligible variations exist in the evaluations of these scenarios when using the standard or extended versions of Maelia. Using the extended version of Maelia to implement the strategic decision-making methods introduced in chapters 3 and 4 is not manageable. It would require all 1500 points to be simulated with the extended version of Maelia for the multi-criteria decision-making method introduced in chapter 3 and simulations to run at each iteration of the branch and cut algorithm behind the multi-objective optimization method presented in chapter 4. Since operational simulations of WEFN systems take from 1 to 5 days to run (see Table 15), the above is not viable. The above is possible with the standard version of Maelia because once the reference agricultural scenario has been simulated at operational level with the standard Maelia, and the performance indicator processing workflows of the three uniform regional scenarios (100% Agro, 100% PV, Agrivoltaïcs) have been run, other non-uniform land-use allocation scenarios can be characterized in less than a minute. We thus recommend the use of our multi-actor multi-level framework with the standard version of Maelia to find optimal WEFN scenarios that account for multi-actor multi-sector objectives. We recommend the use of the extended version of Maelia to simulate the optimal scenarios obtained from our framework to achieve better characterizations of the scenarios by computing WEFN performance indicators based on output data of operational simulations of complete WEFN systems. Figure 22 illustrates our recommendations.

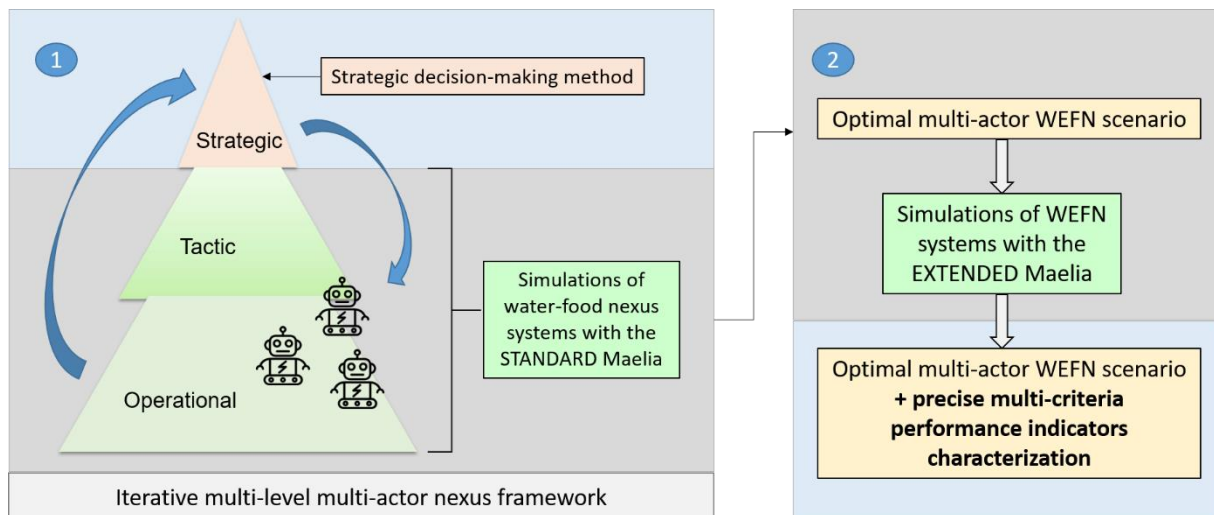


Figure 22: Recommendations for the use of the standard and extended versions of Maelia

VI. Conclusion and perspectives

To conclude this chapter has introduced and tested the use of an extended version of the multi-agent based platform, Maelia, whose standard version has been used in chapters 3 and

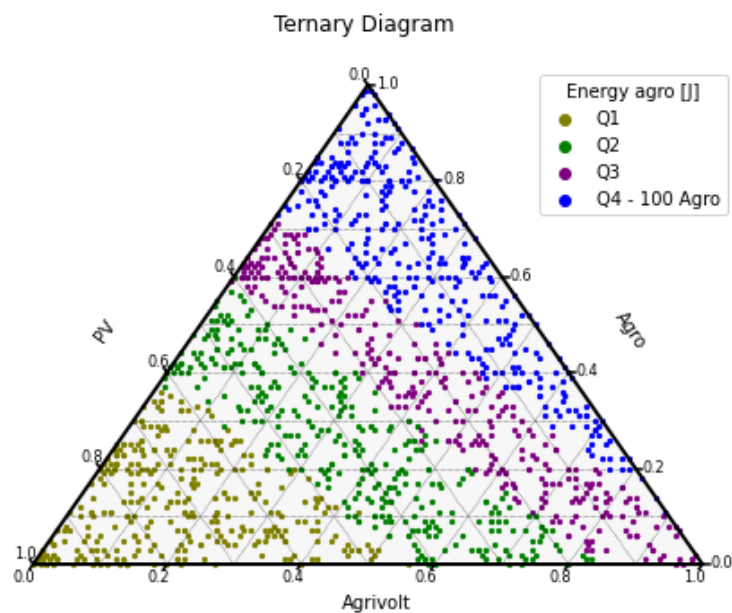
4 to implement our multi-actor multi-level nexus framework. The standard version of Maelia simulates water-food systems at operational scales (parcel level and daily time step). It has been coupled in chapters 3 and 4 with strategic decision-making methods to produce optimal scenarios with respect to multi-sector and multi-actor criteria. This chapter has introduced and tested an extended version of Maelia that simulates the installation of solar panels in agricultural land. It simulates the impact the installation of solar panels in agricultural land has on the territory water resource. Solar panels impede water that is normally evapotranspired by crops when the plot is fully covered with crops to leave the land and therefore this water stays in the water resource system. We have analysed and compared the characterization of two uniform regional scenarios, seven land-use allocation points characterized by given percentages of parcels covered with given WEFN land-use alternatives, two expert scenarios and two 50-50 scenarios that cover 50% of the land with solar panels in two different ways with the standard and extended versions of Maelia. Results have evidenced significant variations in performance indicators. Agricultural yields are highly overestimated and the LWRF [days] indicator is strongly underestimated with the standard version of Maelia. This evidences the importance of using the extended version of Maelia to correctly characterize the state of the water resource at territory level for WEFN nexus scenarios in agricultural land. The extended version of Maelia has been used to design and simulate expert WEFN land-use allocation scenarios and they have been compared to the solution of our multi-level multi-actor framework implemented with the standard version of Maelia in previous chapters. Results show that expert scenarios sketched to guarantee territory electricity, food caloric and protein autonomies benefit more agricultural production and environmental footprint reduction. The solution of our multi-actor multi-level framework guarantees higher electricity production and better water resource state, but it does not ensure territory protein autonomy. Strategic trade-offs illustrated between the expert scenarios and the solution of our multi-level multi-actor framework show the importance of designing methodological tools such as our framework to serve as neutral tools that can ease communication among nexus actors with conflicting views. The simulation of scenarios that cover 50% of the territory agricultural land with solar panels in two different ways has evidenced that the location of solar panels does influence the nexus territory state. It has also validated our initial hypothesis according to which installing solar panels in the northern part of an agricultural territory has a positive impact on southern crop yields. This analysis has also evidenced that simulating complete WEFN systems at operational level enables simulating the intrinsic link that exists across agricultural parcels through the water resource. We recommend using the standard version of Maelia to implement our multi-level multi-actor framework that produces optimal multi-actor multi-sector solutions. We then recommend the use of the extended version of Maelia to simulate the optimal scenarios derived from our framework to obtain more precise nexus performance indicators and to better characterize the state of the water resource at territory level.

VII. References

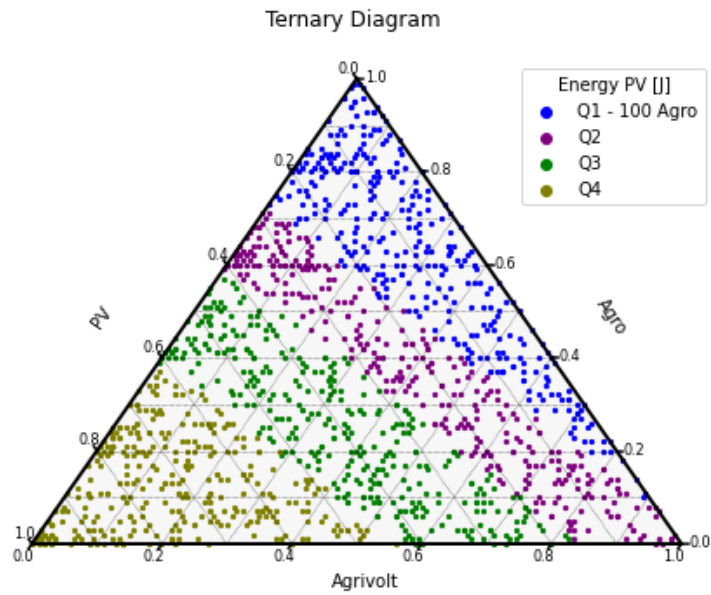
- L'Observatoire des Territoires, 2020. Population au dernier recensement [WWW Document]. URL <https://www.observatoire-des-territoires.gouv.fr/population-au-dernier-recensement> (accessed 1.11.24).
- ORE, 2021. Consommation annuelle d'électricité et gaz par commune et par secteur d'activité [WWW Document]. URL <https://opendata.agenceore.fr/explore/dataset/conso-elec-gaz-annuelle-par-secteur-dactivite-agregee-commune/> (accessed 3.5.23).
- Tribouillois, H., Constantin, J., Murgue, C., Villerd, J., Therond, O., 2022. Integrated modeling of crop and water management at the watershed scale: Optimizing irrigation and modifying crop succession. *Eur. J. Agron.* 140, 126592. <https://doi.org/10.1016/j.eja.2022.126592>

VIII. Appendices

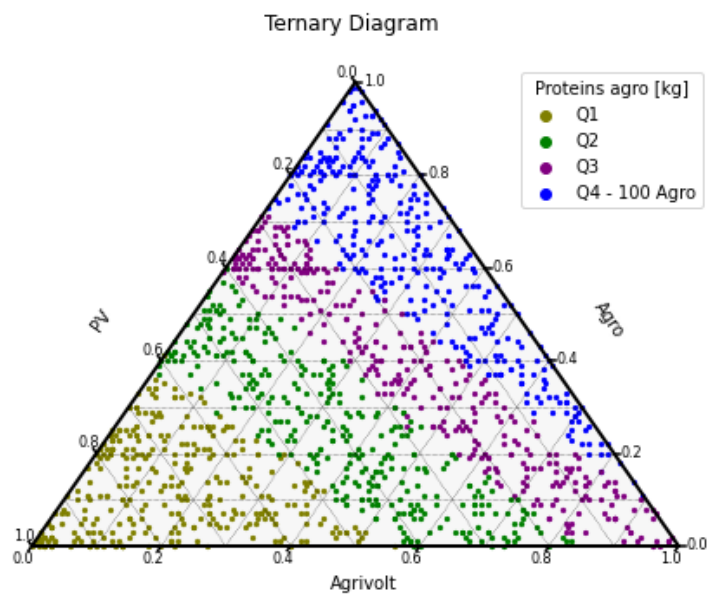
- a. Appendix A: Ternary diagram with sample points of WEFN land-use allocation scenarios coloured according to performance indicator quartiles they belong to
- Ternary diagram with sample points coloured according to the Energy agro [J] quartile they belong to :



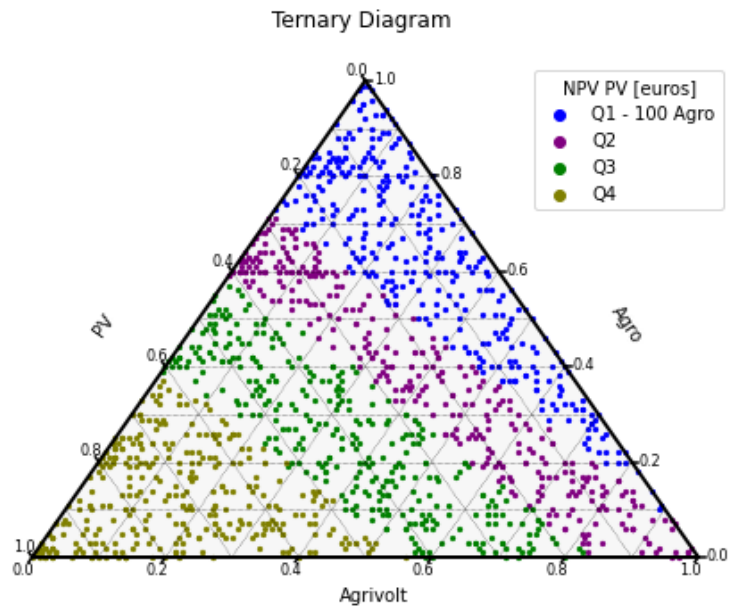
- Ternary diagram with sample points coloured according to the Energy PV [J] quartile they belong to :



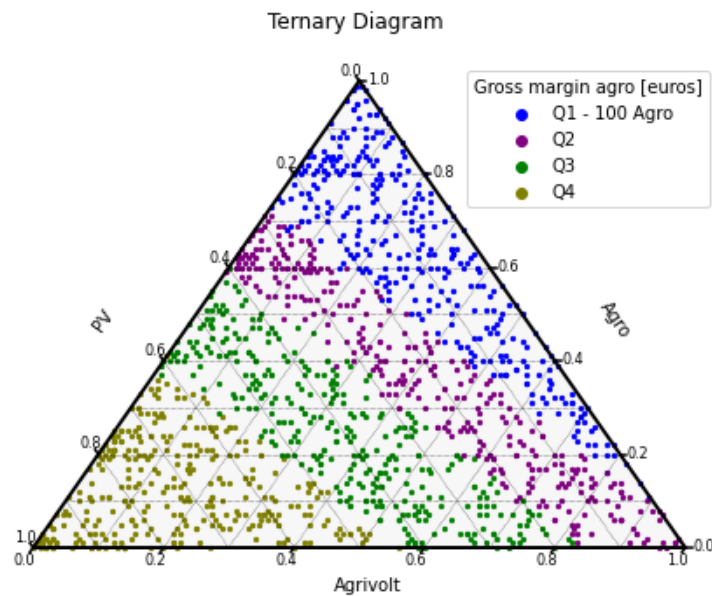
- Ternary diagram with sample points coloured according to the Proteins agro [kg] quartile they belong to :



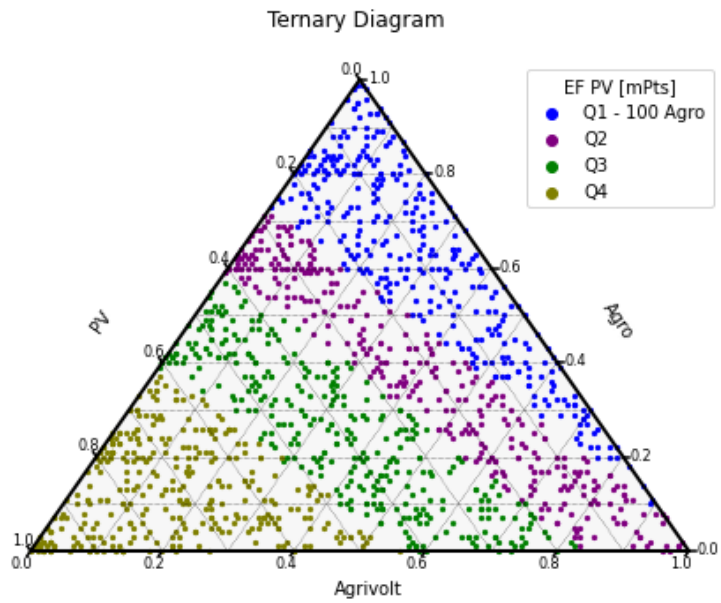
- Ternary diagram with sample points coloured according to the NPV (net present value) PV [euros] quartile they belong to :



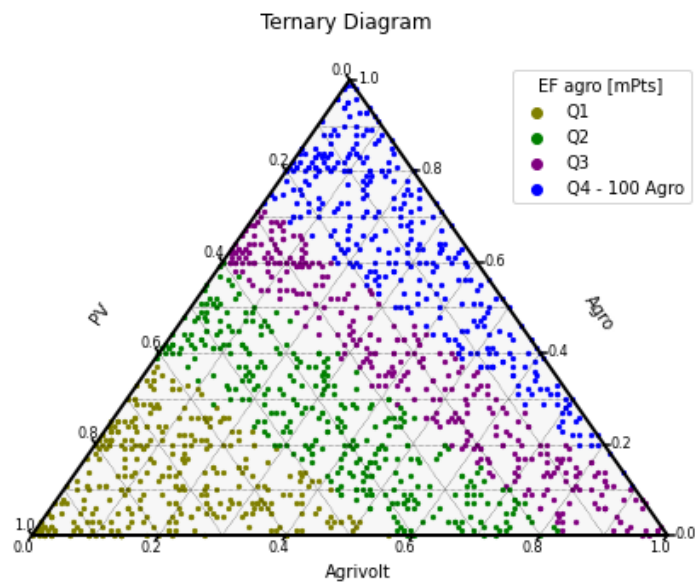
- Ternary diagram with sample points coloured according to the gross agricultural margin [euros] quartile they belong to :



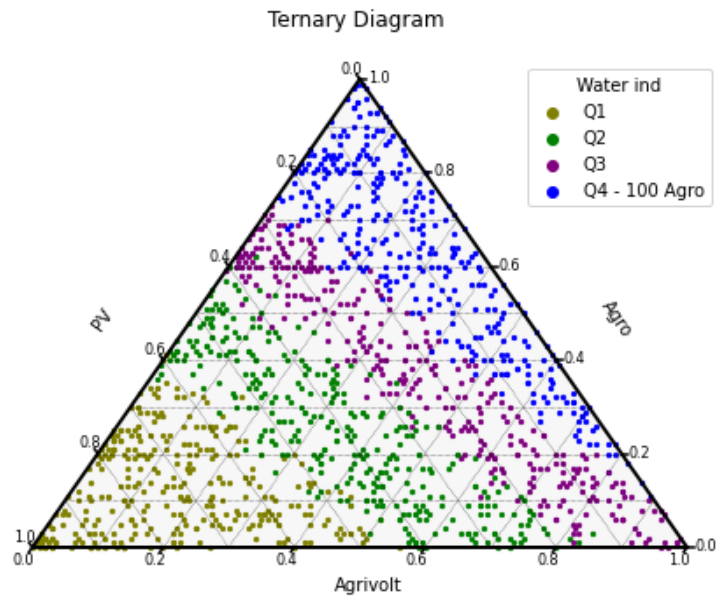
- Ternary diagram with sample points coloured according to the EF PV [mPts] quartile they belong to :



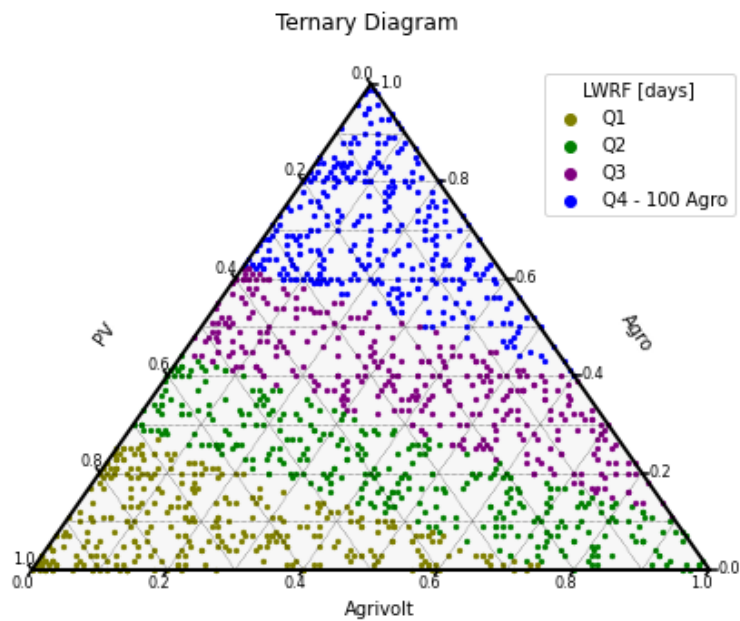
- Ternary diagram with sample points coloured according to the EF agro [mPts] quartile they belong to :



- Ternary diagram with sample points coloured according to the Water indicator quartile they belong to :



- Ternary diagram with sample points coloured according to the LWRF [days] quartile they belong to :



b. Appendix B: Performance indicator values of the twenty one scenarios simulated with the new Maelia

Scenario nb	Scenario	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]

0	Point_1_v2	2.21E+16	8.77E+17	1.56E+08	8.59E+09	2.89E+08	-	7.77E+09	7.87E+07	2.40E+08	874	4.66E+05
1	Point_1_v1	2.19E+16	8.82E+17	1.55E+08	8.63E+09	2.86E+08	-	7.81E+09	7.86E+07	2.41E+08	876	4.61E+05
2	Point_1_v0	2.18E+16	8.87E+17	1.54E+08	8.68E+09	2.87E+08	-	7.85E+09	7.85E+07	2.38E+08	868	4.59E+05
3	Point_2_v0	2.08E+16	1.01E+18	1.47E+08	9.91E+09	2.63E+08	-	8.97E+09	7.14E+07	2.35E+08	874	4.33E+05
4	Point_2_v2	2.06E+16	1.02E+18	1.45E+08	9.97E+09	2.65E+08	-	9.02E+09	7.06E+07	2.35E+08	870	4.24E+05
5	Point_2_v1	2.04E+16	1.02E+18	1.44E+08	1.00E+10	2.59E+08	-	9.04E+09	7.10E+07	2.33E+08	854	4.22E+05
6	Point_3_v2	1.88E+16	1.16E+18	1.34E+08	1.13E+10	2.39E+08	-	1.02E+10	6.34E+07	2.11E+08	868	3.82E+05
7	Point_3_v0	1.89E+16	1.16E+18	1.33E+08	1.14E+10	2.38E+08	-	1.03E+10	6.31E+07	2.05E+08	856	3.82E+05
8	Point_3_v1	1.93E+16	1.17E+18	1.36E+08	1.14E+10	2.39E+08	-	1.04E+10	6.36E+07	2.14E+08	858	3.89E+05
9	Point_4_v2	1.77E+16	1.29E+18	1.25E+08	1.26E+10	2.18E+08	-	1.14E+10	5.70E+07	1.99E+08	858	3.51E+05
10	Point_4_v0	1.78E+16	1.29E+18	1.25E+08	1.26E+10	2.22E+08	-	1.14E+10	5.77E+07	2.17E+08	856	3.55E+05
11	Point_4_v1	1.78E+16	1.29E+18	1.26E+08	1.27E+10	2.23E+08	-	1.15E+10	5.75E+07	2.06E+08	858	3.58E+05
12	Point_5_v1	1.70E+16	1.35E+18	1.21E+08	1.32E+10	2.10E+08	-	1.20E+10	5.32E+07	1.87E+08	854	3.38E+05
13	Point_5_v2	1.67E+16	1.36E+18	1.18E+08	1.33E+10	2.04E+08	-	1.21E+10	5.22E+07	1.76E+08	836	3.30E+05
14	Point_6_v0	1.72E+16	1.37E+18	1.21E+08	1.34E+10	2.05E+08	-	1.21E+10	4.94E+07	2.10E+08	862	3.29E+05
15	Point_6_v2	1.75E+16	1.38E+18	1.23E+08	1.35E+10	2.02E+08	-	1.22E+10	5.13E+07	1.91E+08	850	3.34E+05
16	Point_5_v0	1.69E+16	1.38E+18	1.18E+08	1.35E+10	2.06E+08	-	1.23E+10	5.34E+07	1.85E+08	848	3.32E+05
17	Point_6_v1	1.67E+16	1.40E+18	1.18E+08	1.37E+10	1.99E+08	-	1.24E+10	5.00E+07	1.87E+08	844	3.23E+05
18	Point_7_v2	1.19E+16	1.75E+18	8.33E+07	1.71E+10	1.42E+08	-	1.55E+10	3.51E+07	1.27E+08	812	2.23E+05
19	Point_7_v0	1.21E+16	1.76E+18	8.46E+07	1.72E+10	1.38E+08	-	1.56E+10	3.41E+07	1.31E+08	824	2.29E+05

20	Point_7_v1	1.17E+16	1.76E+18	8.28E+07	1.72E+10	1.35E+08	1.56E+10	3.43E+07	1.23E+08	814	2.25E+05
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c. Appendix C: Performance indicator values of the twenty one scenarios simulated with the new Maelia but characterized with outputs of the old Maelia combined with food and water hypotheses

Scenario nb	Scenario	Energy agro [J]	Energy PV [J]	Proteins agro [kg]	NPV PV [euros]	Gross margin agro [euros]	EF PV [mPts]	EF agro [mPts]	Water ind	LWRF [days]	Farmer labor [h]
0	Point_1_v2	2.63E+16	8.77E+17	1.84E+08	8.59E+09	-2.84E+08	7.77E+09	7.05E+07	3.06E+08	377.18	4.76E+05
1	Point_1_v1	2.60E+16	8.82E+17	1.82E+08	8.63E+09	-2.81E+08	7.81E+09	7.04E+07	3.02E+08	377.18	4.70E+05
2	Point_1_v0	2.61E+16	8.87E+17	1.82E+08	8.68E+09	-2.83E+08	7.85E+09	7.03E+07	3.05E+08	377.21	4.69E+05
3	Point_2_v0	2.45E+16	1.01E+18	1.71E+08	9.91E+09	-2.59E+08	8.97E+09	6.48E+07	2.88E+08	370.56	4.41E+05
4	Point_2_v2	2.43E+16	1.02E+18	1.69E+08	9.97E+09	-2.61E+08	9.02E+09	6.43E+07	2.93E+08	370.53	4.33E+05
5	Point_2_v1	2.39E+16	1.02E+18	1.67E+08	1.00E+10	-2.54E+08	9.04E+09	6.44E+07	2.87E+08	370.56	4.31E+05
6	Point_3_v2	2.17E+16	1.16E+18	1.53E+08	1.13E+10	-2.35E+08	1.02E+10	5.88E+07	2.53E+08	363.88	3.91E+05
7	Point_3_v0	2.19E+16	1.16E+18	1.52E+08	1.14E+10	-2.35E+08	1.03E+10	5.85E+07	2.48E+08	363.91	3.90E+05
8	Point_3_v1	2.22E+16	1.17E+18	1.54E+08	1.14E+10	-2.35E+08	1.04E+10	5.88E+07	2.56E+08	363.88	3.96E+05
9	Point_4_v2	2.01E+16	1.29E+18	1.41E+08	1.26E+10	-2.13E+08	1.14E+10	5.37E+07	2.31E+08	358.54	3.59E+05
10	Point_4_v0	2.02E+16	1.29E+18	1.40E+08	1.26E+10	-2.18E+08	1.14E+10	5.43E+07	2.49E+08	358.54	3.62E+05
11	Point_4_v1	2.04E+16	1.29E+18	1.43E+08	1.27E+10	-2.19E+08	1.15E+10	5.42E+07	2.44E+08	358.54	3.66E+05
12	Point_5_v1	1.88E+16	1.35E+18	1.32E+08	1.32E+10	-2.06E+08	1.20E+10	5.14E+07	2.09E+08	368.33	3.45E+05
13	Point_5_v2	1.85E+16	1.36E+18	1.29E+08	1.33E+10	-2.00E+08	1.21E+10	5.03E+07	2.00E+08	368.33	3.37E+05
14	Point_6_v0	1.85E+16	1.37E+18	1.30E+08	1.34E+10	-2.01E+08	1.21E+10	4.88E+07	2.26E+08	396.74	3.35E+05
15	Point_6_v2	1.87E+16	1.38E+18	1.31E+08	1.35E+10	-1.99E+08	1.22E+10	5.05E+07	2.03E+08	396.74	3.40E+05
16	Point_5_v0	1.85E+16	1.38E+18	1.29E+08	1.35E+10	-2.01E+08	1.23E+10	5.12E+07	2.05E+08	368.33	3.38E+05
17	Point_6_v1	1.79E+16	1.40E+18	1.26E+08	1.37E+10	-1.94E+08	1.24E+10	4.90E+07	2.00E+08	396.74	3.30E+05
18	Point_7_v2	1.30E+16	1.75E+18	9.04E+07	1.71E+10	-1.39E+08	1.55E+10	3.45E+07	1.42E+08	268.48	2.29E+05
19	Point_7_v0	1.31E+16	1.76E+18	9.12E+07	1.72E+10	-1.35E+08	1.56E+10	3.35E+07	1.43E+08	268.48	2.35E+05
20	Point_7_v1	1.28E+16	1.76E+18	8.97E+07	1.72E+10	-1.33E+08	1.56E+10	3.38E+07	1.36E+08	268.48	2.31E+05

Chapter 6: Conclusion and perspectives

I. Conclusion

Population growth, globalization and climate change are jeopardizing water, energy and food securities worldwide. Local, national and international recommendations and objectives are set and shared to guide stakeholders and scientists initiatives to tackle climate change and prevent resources conflicts. At international level, the Paris Agreement was established in 2015 by 196 countries with the main goal of limiting global warming well under 2°C when compared to pre-industrial temperatures. To respect this goal, countries are encouraged to embark on a journey of GHG emissions reduction. The same year, the United Nations established 17 Sustainable Development Goals (SDGs) that countries must consider to define their strategies and development plans. The 17 SDGs recognize economic, social and environmental concerns. Goals 2 ('zero hunger'), 6 ('clean water and sanitation') and 7 ('affordable and clean energy') address food, water and energy resources respectively. The Nexus approach was conceptualized in 2011 as a way to consider interdisciplinary and transdisciplinary interactions of water, food and energy resources. The interdisciplinary dimension refers to synergies and trade-offs that exist among resources at varied temporal and spatial scales. The transdisciplinary dimension addresses multi-actor and multi-sector objectives and perspectives at varied decision levels on the same system. The scientific community claims a nexus approach is a must-have to address water, energy and food management problems. The Process Systems Engineering (PSE) community studies multi-scale complex physicochemical systems and develops simulation, optimization and control methodologies and tools to address resource and society present and future needs and challenges (Pistikopoulos et al., 2021). The PSE community has therefore its role to play in developing tools to better manage Water-Energy-Food Nexus systems.

Chapter 1 has introduced the economic, environmental and scientific contexts around Water-Energy-Food systems. The scientific context shared is strongly inspired from a published exhaustive literature review on existing multi-actor integrated approaches for water-energy-food nexus systems (Bois et al., 2024). The review has classified sixty-two articles into mathematical modelling approaches, participatory approaches, multi-criteria decision-making approaches and mixed approaches. It has evidenced the lack of multi-actor multi-level bottom-up approaches where operational and tactical conditions constrain strategic solutions. Multi-agent based modelling is so far the only technique that enables simulation of nexus interactions among resources and between resources and actors of the system at operational (daily and small spatial entity scale such as agricultural plot scale) scales. Previous studies among the PSE community have recommended their use (Peña-Torres et al., 2022). The scientific exhaustive review recommends the use of participatory approaches to co-design tactical or strategic scenarios and to select or develop performance indicators. Previous PSE studies have also recommended the use of new modelling paradigms and participatory

modelling approaches (Gerbaud, 2023). The literature review advises the use of multi-objective optimization, game theory or fractional programming to solve multi-actor resource allocation conflicts and the use of multi-criteria decision-making to perform multi-actor multi-sector integrated nexus assessment. We have chosen to develop a bottom-up multi-actor multi-level framework for water-energy-food systems that combines multi-agent based simulations with strategic multi-criteria decision-making methods or strategic multi-objective optimization and to implement it for land-use allocation problems in agricultural land at parcel spatial scale. Combining different modelling techniques enables finding solutions that satisfy multi-actor objectives at varied decision-levels and that are operationally viable. Such frameworks imply switching from the traditional PSE top-down approach where the strategic decision level imposes tactical and operational solutions to an innovative bottom-up approach where the operational decision-level constrains tactical and strategic solutions.

Chapter 2 has briefly introduced the generic iterative multi-level multi-actor framework designed for water-energy-food nexus systems. The framework is generic because it combines multi-agent based simulations with strategic decision-making methods, which are both generic. The framework is iterative because it iterates between strategic, operational and tactical decision levels to generate nexus scenarios that satisfy multi-level and multi-actor constraints and objectives. For agricultural land-use allocation problems, the operational scale comprises the agricultural parcel and a daily time step, the tactical scale farms and cropping seasons and the strategic scale simulates territory and yearly dynamics and objectives. The novelty of our multi-level multi-actor WEFN framework resides in accounting for geographical dependencies at operational scales and simulating nexus actors at operational, tactical and strategic decision levels. MAELIA is used to simulate operational nexus scenarios of our French case study territory. MAELIA (Therond et al., 2014) ('Modelling of socio-Agro-Ecological systems for Landscape Integrated Assessment') is a multi-agent based platform launched in 2009 by French researchers to assess socio-economic and environmental impacts of agricultural practices at territorial scale. MAELIA can be applied to any agricultural territory for which the required input data is available. Input data needed to run the multi-agent based models comprises graphic parcel register datasets, soil, hydrology and meteorological datasets. It also includes economic and social data such as crop selling prices, costs or working hours associated to given technical agricultural operations. If all this data is available, the multi-agent based model selected for our framework can be applied to any type of territory. The same stands for the strategic decision-making methods designed. They are based on the evaluation of generic WEFN performance indicators, which can be computed as long as the necessary input data is available. No extra data from the input data required for the multi-agent based simulations is needed to calculate nexus performance indicators. Ten resource production, economic, environmental and social multi-sector and multi-actor performance indicators have been established to evaluate sustainability and synergy of scenarios simulated with MAELIA. Methodologies that rely on QGIS, pyQGIS and open datasets have been designed to determine agricultural land that is suitable for solar panels and wind turbines in terms of

geographical feasibility and regulation compliance. These are needed for our framework to only simulate WEFN scenarios that are physically and legislatively feasible. Information shared on nexus performance indicators in chapter 2 can be partly found in a congress article published in the journal of the Italian Association of Chemical Engineering on the occasion of the 2nd international conference on energy, environment and digital transition held in Palermo, Italy in October 2023 (Saint-Bois et al., 2023).

Chapter 3 has introduced an exploratory and stochastic Monte Carlo and multi-criteria decision-making based approach developed to design strategic decision-making methods for our multi-level multi-actor WEFN framework. AHP (Analytic Hierarchy Process) is used as the multi-criteria decision-making method. One local (parcel level) and two regional (watershed level) decision-making methods have been designed with this approach. They have been implemented for the French case study territory selected to illustrate this PhD work. The case study territory is situated downstream the Aveyron's river watershed located south of France and is about 800 km² and accounts with about 15000 parcels. It has been selected because it faces water stress and MAELIA has been calibrated and validated for this territory. The three stochastic multi-criteria decision-making approaches developed produce the same result: the 100% PV land-use alternative is the best with respect to the multi-criteria performance indicators selected at both parcel and regional levels. It would be interesting to simulate scenarios with agricultural governmental subsidies to see how solutions are impacted. The work presented in chapter 3 has been shared in an article published in Computers and Chemical Engineering journal (Saint-Bois et al., 2024).

Chapter 4 has implemented a deterministic multi-objective approach that is more similar to traditional PSE (Process and Systems Engineering) approaches to test its use and efficiency as a strategic decision-making method for our multi-actor multi-level WEFN framework. The approach is applied for the same case study territory as the one used to illustrate Chapter 3. Mixed Integer Linear programming (MILP) is combined with Goal Programming and IBM's ILOG CPLEX optimization studio is used to model and solve the problem. Goal programming is used because a criteria sensibility analysis has validated the goal defined from expert knowledge. Results from the deterministic multi-objective optimization approach are the same as those found with the stochastic multi-criteria decision-making approach detailed in Chapter 3. For our case study territory, when equal importance is given to all performance indicators, covering all agricultural land that is suitable for solar panels with solar panels results in optimized parcel and territory performance indicators. Chapter 4 has shown that the stochastic exploratory approach developed in Chapter 3 is more easily applied than the multi-objective deterministic approach and is applicable to a wider range of territory sizes.

Chapter 5 has introduced an extended version of Maelia that enables simulating WEFN scenarios that allocate solar panels in agricultural land at operational scales. The extended version of Maelia simulates water resource dynamics at operational parcel level. It simulates the fact that water that is evapotranspired in a plot under the reference agricultural scenario stays in the territory watercourses if a solar panel is installed on that plot. Agricultural parcels

are therefore intrinsically linked through the water resource. The LWRF [days] indicator enables evaluating the resulting water resource state at territory level. Simulating regional uniform scenarios with the extended version of Maelia and the study of scenarios that represent a compromise between uniform regional scenarios covering all plots with 100% Agro or 100% PV land-use alternatives have shown that the extended version of Maelia is mostly needed to correctly evaluate the territory water LWRF [days] indicator. LWRF [days] indicates the number of days the territory's main watercourse's flow goes under a given legislative threshold. The simulation of expert scenarios sketched with the aim of transitioning towards autonomous territories in terms of food and electricity has shown that they are very different from the scenario obtained from the use of our multi-level multi-actor nexus framework. Indeed, a 100% PV uniform regional scenario is obtained with our multi-level multi-actor framework for the French case study territory selected to illustrate our framework. Multi-actor and multi-sector trade-offs exist between the expert scenarios and the solution of our framework. Therefore, our framework comes as a methodological support tool to help different nexus stakeholders to engage in difficult conversations regarding territories development plans and strategies. The study of two 50-50 scenarios has illustrated that the location of solar panels affects territory strategic performance indicators. Moreover, the study of the two 50-50 scenarios has validated our initial hypothesis according to which installing solar panels in the northern part of the territory results in higher southern crop yields. We recommend using the standard version of Maelia to implement our multi-actor multi-level WEFN nexus framework to produce optimal nexus resource management scenarios that respect operational geographical, meteorological and nexus actors social constraints. We then recommend the use of the extended version of Maelia to better characterize nexus performance strategic indicators and specifically to better evaluate the state of the water resource at territory level for WEFN scenarios that allocate solar panels in agricultural land.

Figure 1 illustrates the methodological steps that must be followed to implement our approach for other agricultural territories. Our approach enables studying WEFN nexus systems and finding resource management solutions that respect operational constraints and consider multi-actor and multi-sector objectives. Our approach can be implemented with Maelia as the multi-agent based integrated platform if the necessary input data to parametrize and run Maelia is available or can be gathered and collected. Input data needed to run Maelia comprises graphic parcel register datasets, soil, hydrology and meteorological datasets. It also englobes economic and social data such as crop selling prices, costs or working hours associated to given agricultural technical operations. Figure 1 shows that to implement our approach for another agricultural territory the first step consists in demarcating the case study territory. The second step consists in gathering the necessary input data and in leading an agricultural land suitability study for solar panels and wind turbines to identify zones on which renewable energy production units can or cannot be installed with respect to geographical and legislative constraints. The third step consists in defining WEFN scenarios and more precisely uniform land-use allocation scenarios if our generic multi-level framework is applied for land-use allocation problems, as it is the case for the present manuscript. Uniform land-

use allocation scenarios allocate the same land-use alternative to every plot of the territory. The fourth step consists in simulating and characterizing the uniform regional scenarios with the standard version of Maelia coupled with water and food hypotheses to evaluate the impact of solar land-use alternatives on food and water. The fifth step computes multi-sector multi-actor nexus performance indicators. The sixth step runs strategic decision-making methods to produce optimal nexus scenarios that satisfy operational constraints. The seventh step uses the extended version of Maelia to simulate optimal nexus scenarios produced in the sixth step and the eighth step computes nexus performance indicators of scenarios simulated with the extended version of Maelia. Implementing our multi-actor multi-level framework shown in Figure 1 results in an optimal WEFN resource management scenario that accounts for operational nexus constraints and considers strategic multi-actor and multi-sector objectives.

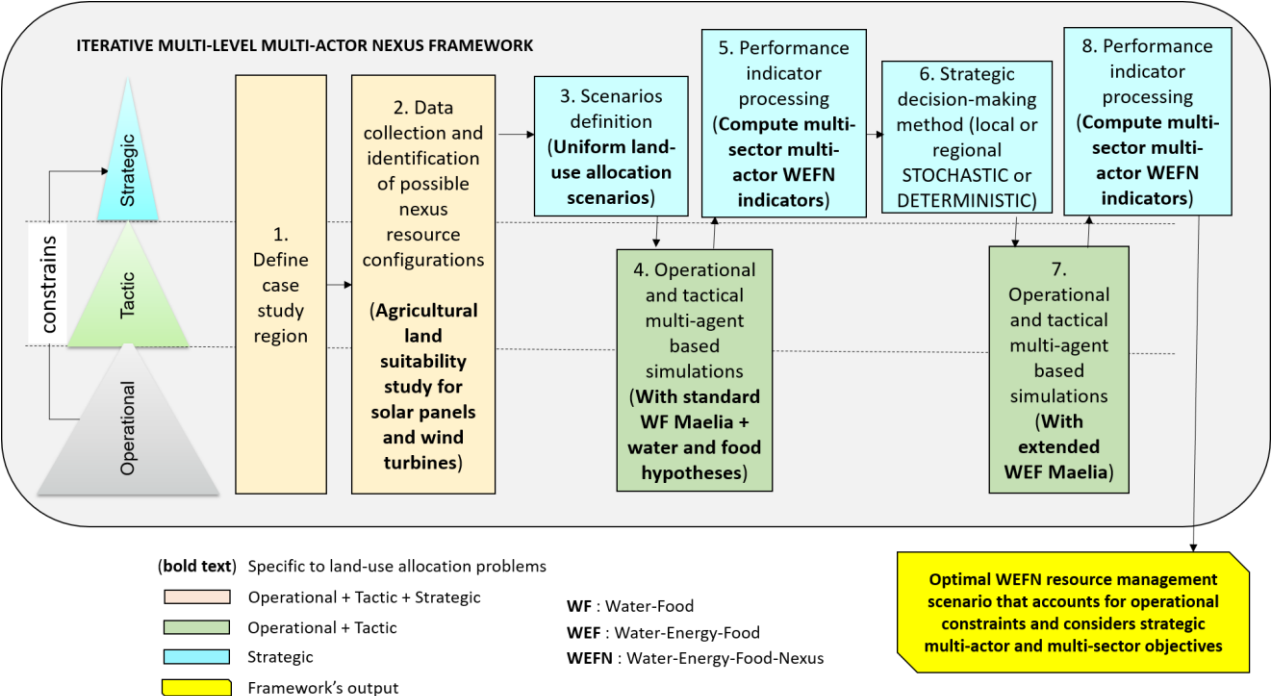
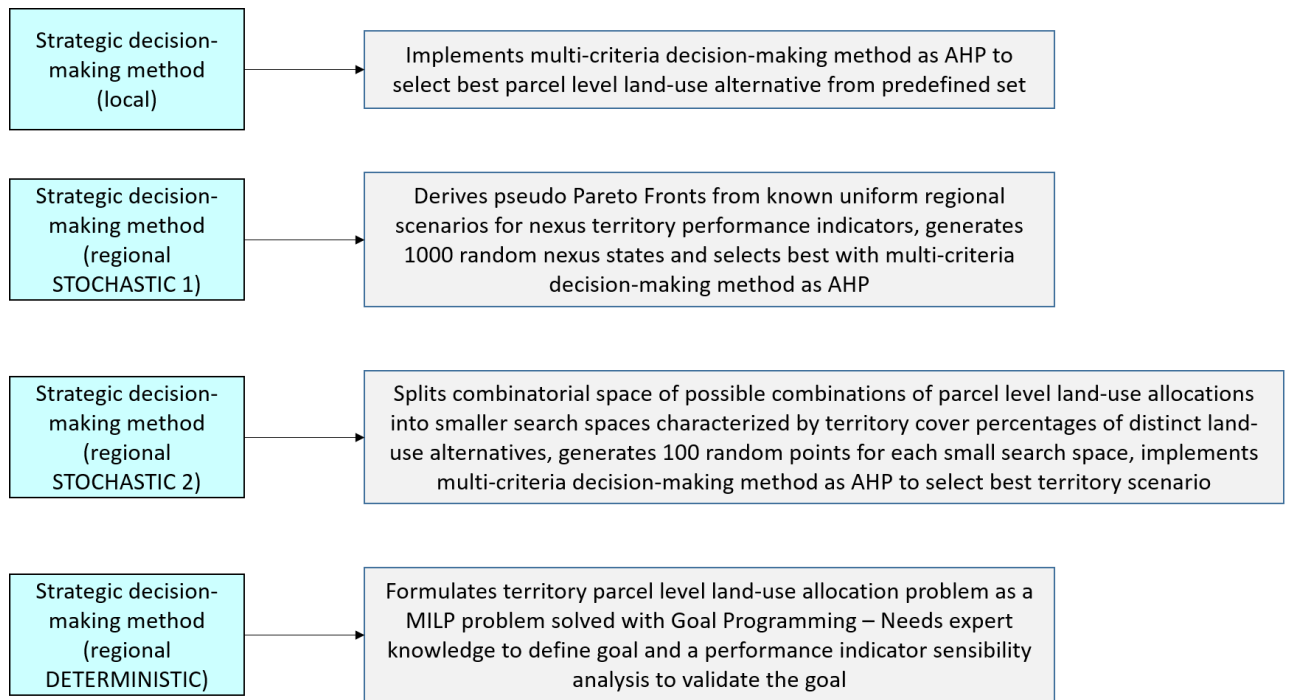


Figure 1: Methodological workflow to apply our generic iterative multi-level multi-actor nexus framework designed to ease communication among nexus actors with confronting views and objectives

Figure 2 recapitulates the distinct local and regional strategic decision-making methods that can be applied in step 6 of the methodological workflow shown in Figure 1. Table 1 displays the use recommendations for each of them and their respective advantages and disadvantages.



AHP : Analytic Hierarchy Process
MILP : Mixed Integer Linear Programming

Figure 2: Summary of the four strategic decision-making methods designed for our multi-level multi-actor nexus framework

Table 1: Recommendations, advantages and drawbacks of the four strategic decision-making methods developed for our multi-level multi-actor nexus framework

Strategic decision-making method	Recommendations	Advantages	Drawbacks
Local	Use it for parcel level decision-making	Simple and quick to implement	Does not account for interactions between neighboring parcels of an entire territory linked through nexus resources
Regional stochastic 1	Use it to identify best regional uniform scenario from those known	Simple and quick to implement	Does not allocate specific land-use alternatives to parcels Does not accurately predict regional performance indicator values
Regional stochastic 2	Use it to find good compromise solution for large size territories (around 1500 parcels)	Always finds a good compromise solution Allocates specific land-use alternatives to parcels No expert knowledge is needed	Does not guarantee to find an optimal solution Long computation time (around 6 hours) Limited computationally as the number of parcels increases

Regional deterministic	Use it to find optimal solutions for small size territories (less than 1000 parcels)	Allocates specific land-use alternatives to parcels Finds local optimum	Does not guarantee global optimum Needs expert knowledge to define the goal and a performance indicators sensibility analysis to validate the goal
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The bottom-up approach enabled by our multi-level multi-actor framework is a novelty with respect to traditional top-down approaches implemented in our PSE (Process and Systems Engineering) community. Table 2 lists advantages and drawbacks of both top-down and bottom-up approaches for nexus systems. The main advantage of our bottom-up approach is that it simulates operational nexus dynamics and physical, geographical and social constraints at operational level at the same time it considers strategic multi-sector and multi-actor confronting objectives to find resource management solutions. The main disadvantage is that it is very data intensive, meaning that it cannot be run if precise agricultural and hydrological data is not available. Collecting and creating agricultural and hydrological data needed to run integrated multi-agent based simulations can take several months and may require installing new data recording infrastructures such as new equipment to measure water flows and levels.

Table 2: Advantages and drawbacks of top-down vs bottom-up approaches for nexus systems

	Advantages	Drawbacks
<u>Top-down</u> : Strategic imposes operational	Quick to implement in terms of computational time Easy to implement in terms of data and software needed	Operational dynamics and actor's objectives are not accounted for, which reduces the acceptability and operability of the operational solutions derived from the strategic solutions
<u>Bottom-up</u> : Operational imposes strategic	Accounts for operational nexus dynamics and actor's objectives, so multi-level solutions deduced are therefore more easily accepted by all actors of nexus systems	Data intensive and long computation times More laborious methodological frameworks that require more software

Because our approach is data intensive, we recommend leading a traditional top-down approach first. We only recommend using our approach if solutions obtained with traditional top-down approaches do not provide enough information to enable their implementations at territory or local scales or if they are not accepted by all nexus actors.

II. Perspectives

This section presents future perspectives for our work. The first perspective is to simulate scenarios with positive agricultural governmental subsidies to see how resulting non-negative agricultural margins would shift our framework's results. The second perspective is to improve

the social indicators used for our multi-actor strategic decision-making methods. This involves the inclusion of a social indicator that accounts for work hours spent by energy related actors installing and maintaining renewable energy generation units. This would reinforce the multi-actor aspect of our framework since in its present state only a social indicator that accounts for farmers' work is included. Additionally a social indicator that measures the will of nexus actors to accept new land-use allocation alternatives could be added. Roger's innovation adoption curve could be used as a probability curve to evaluate nexus actors' wills to accept energy related land-use alternatives at parcel level. Another perspective is to consider new land-use allocation alternatives such as wind turbines, biomass or farm related land-use alternatives for territories where these alternatives are possible. It would be interesting to apply our framework to new case study territories to confront solutions obtained with our framework and expert scenarios and to evaluate to what extent our framework facilitates stakeholders' discussions. Moreover, we could examine additional ways in which farmers could benefit from renewable energy production systems. Instead of assuming that renewable energy production economic gains come from electricity that is not purchased from the power grid because it is locally produced, we could model energy related actors paying monthly rents to farmers. We could also use our framework coupled with the standard and extended versions of Maelia to investigate how agricultural and energy systems in agricultural land will react to future climate scenarios by using predictive meteorological datasets such as the RCP scenarios' datasets.

The main perspective for our work is to develop a multi-actor strategic decision-making method for our framework based on Game Theory. The advantage of this method with respect to those presented in this manuscript is that it would enable examining more land-use allocation alternatives at parcel level and territories with more plots. With the actual strategic decision-making methods designed for our framework, contemplating more than three land-use allocation alternatives per plot causes convergence issues because of out of memory problems. The problem has been exposed and discussed with Tristan Cazenave, a French researcher based in Paris, France and working in the LAMSADE lab. He has suggested applying a game theory method to find Pareto Fronts for our systems. To implement the game theory method, a previous step must show that at parcel level, not allocating the land-use alternative for which the individual objective is the best, results in a bettered global objective. Figure 3 illustrates the problem with a farmer actor and a solar related actor, which compete to allocate their respective land-use alternatives at plot level. For nexus systems, a global water objective is set since both actors aspire to optimize water resource state.

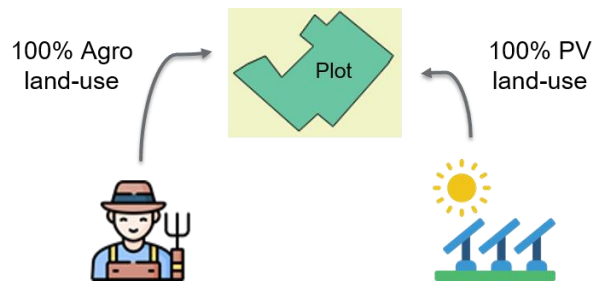


Figure 3: Problem illustration for game theory multi-actor strategic decision-making method

Once the Pareto Front is drawn by the Game Theory method, the last step of the methodology discussed with Tristan Cazenave applies a multi-criteria decision-making method to select solutions from the Pareto Front. To implement the Game Theory method values taken by individual and global objectives must be known for every plot under the two land-use alternatives compared.

Results obtained with this Game Theory methodology could be compared in terms of computational efficiency and multi-actor satisfaction rates, with previous multi-leader multi-follower approaches implemented in our laboratory (Ramos, 2016) to find equilibrium strategies between actors of eco-industrial parks.

III. References

- Bois, A.S., Boix, M., Montastruc, L., 2024. Multi-actor integrated modeling approaches in the context of Water-Energy-Food Nexus systems: Review. *Comput. Chem. Eng.* 182, 108559. <https://doi.org/10.1016/j.compchemeng.2023.108559>
- Gerbaud, V., 2023. PSE perspective: Paradigm transition towards Complex Thought in a global world under pressure. *Comput. Chem. Eng.* 175, 108274. <https://doi.org/10.1016/j.compchemeng.2023.108274>
- Peña-Torres, D., Boix, M., Montastruc, L., 2022. Optimization approaches to design water-energy-food nexus: A literature review. *Comput. Chem. Eng.* 167, 108025. <https://doi.org/10.1016/j.compchemeng.2022.108025>
- Pistikopoulos, E.N., Barbosa-Povoa, A., Lee, J.H., Misener, R., Mitsos, A., Reklaitis, G.V., Venkatasubramanian, V., You, F., Gani, R., 2021. Process systems engineering – The generation next? *Comput. Chem. Eng.* 147, 107252. <https://doi.org/10.1016/j.compchemeng.2021.107252>
- Ramos, M., 2016. Bilevel optimization of Eco-Industrial parks for the design of sustainable resource networks (phd).
- Saint-Bois, A., Boix, M., Montastruc, L., Therond, O., 2023. Simulating Renewable Energy Production Scenarios Under Water and Food Constraints. *Chem. Eng. Trans.* 105, 457–462. <https://doi.org/10.3303/CET23105077>
- Saint-Bois, A., Boix, M., Therond, O., Montastruc, L., Villerd, J., Touche, I., 2024. Multi-actor approach to manage the water-energy-food nexus at territory scale. *Comput. Chem. Eng.* 108773. <https://doi.org/10.1016/j.compchemeng.2024.108773>
- Therond, O., Sibertin-Blanc, C., Lardy, R., Gaudou, B., Balestrat, M., Hong, Y., Louail, T., Nguyen, V.B., Panzoli, D., Sanchez-Pérez, J.-M., Sauvage, S., Taillandier, P., Vavasseur, M., Mazzega, P., 2014. Integrated modelling of social-ecological systems: The MAELIA high-resolution multi-agent platform to deal with water scarcity problems. Presented at the 7th International

Environmental Modelling and Software Society (iEMSs 2014), International Environmental Modelling and Software Society, p. 1.

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Titre : Méthodologie d'aide à la décision multi-acteur et multi-échelles pour les systèmes nexus eau-énergie-alimentation

Mots clés : Méthodologie d'aide à la décision, Nexus Eau - Énergie - Alimentation (WEFN), Multi-acteur, Multi-échelles, Modélisation intégrée

Résumé : Cette étude présente une méthodologie générique multi-acteurs et multi-niveaux pour la gestion des systèmes nexus eau-énergie-alimentation. Les systèmes nexus eau-énergie-alimentation sont des systèmes où l'eau, l'énergie et l'alimentation interagissent et présentent des synergies et des compromis à différentes échelles spatiales et temporelles. Leur gestion est menée par des décideurs provenant de secteurs divers, qui interviennent à des niveaux de décision variés. Ces systèmes sont complexes et le niveau opérationnel ne peut être négligé pour concevoir des stratégies de gestion adéquates.

Ce travail présente la première méthodologie destinée aux systèmes nexus eau-énergie-alimentation, qui combine des simulations opérationnelles et intégrées de systèmes multi-agents avec des méthodes d'aide à la décision stratégique. Les simulations à échelles opérationnelles alimentent des outils d'aide à la décision stratégique. La méthodologie a été appliquée à des problèmes d'utilisation des terres à l'échelle de la parcelle agricole. Pour chaque territoire étudié, le nombre de combinaisons possibles d'allocations de stratégies d'utilisation des terres aux parcelles est égal au nombre de stratégies d'utilisation des terres considérées pour chaque parcelle, exponentiel le nombre de parcelles du territoire. Des méthodes d'aide à la décision multicritères basées sur des simulations Monte Carlo ont été conçues afin de pouvoir trouver des solutions de gestion pour des grands territoires (plus de 1000 parcelles) pour lesquels plus de deux stratégies d'utilisation des terres sont considérées sur chaque parcelle. Une méthode d'optimisation multi-objectif a été conçue pour produire des scénarios d'utilisation des terres optimisés à l'échelle du territoire.

La méthodologie a été appliquée à un territoire agricole d'environ 800 km² et 15224 parcelles situé en aval du bassin versant de l'Aveyron en France. Le bassin versant subit du stress hydrique et se trouve dans l'une des régions les plus ensoleillées de France. La production d'énergie renouvelable sur des terres agricoles apparaît comme un moyen de répondre aux objectifs nationaux de production d'énergie renouvelable et de progresser vers des systèmes et des régions agricoles durables. L'installation d'unités de production d'énergie renouvelable sur des terres agricoles confrontées au stress hydrique est une parfaite illustration d'un système nexus eau-énergie-alimentation pour lequel une approche holistique est requise. Les fonctionnalités de la plateforme multi-agents MAELIA (modélisation des systèmes socio-agro-écologiques pour l'évaluation intégrée des paysages), développée par des chercheurs français pour simuler des systèmes agro-hydrologiques complexes, ont été étendues et MAELIA a été utilisée pour simuler la dynamique des systèmes nexus eau-énergie-alimentation au niveau opérationnel. Trois méthodes qui combinent la procédure d'analyse hiérarchique (méthode de prise de décision multicritères) avec des simulations Monte Carlo ont été conçues. La première se base sur des indicateurs à l'échelle de la parcelle pour émettre des décisions locales ; elle sélectionne des stratégies d'utilisation des terres qui optimisent des indicateurs au niveau de la parcelle. Les deux autres méthodes basent leurs prises de décisions sur des indicateurs régionaux. La première identifie le meilleur scénario régional d'utilisation des terres parmi un ensemble de scénarios connus et la deuxième explore l'espace combinatoire des allocations de stratégies d'utilisation des terres à l'échelle de la parcelle et sélectionne une combinaison qui optimise les critères au niveau régional. Une méthode d'optimisation multi-objectif basée sur la programmation linéaire en nombres entiers mixtes (MILP) et la programmation par objectifs a été développée avec le logiciel IBM ILOG CPLEX pour produire des scénarios optimisés à l'échelle régionale, qui allouent des stratégies d'utilisation des terres à l'échelle de la parcelle.

Title: Methodology for multi-actor and multi-scale decision support for Water-Food-Energy systems

Key words: Decision-support approach, Water-Energy-Food Nexus (WEFN), Multi-actor, Multi-scale, Integrated modeling

Abstract: This study presents a generic multi-actor multi-level methodology to optimize the management of water-energy-food nexus systems. Water-energy-food nexus systems are systems where water, energy and food resources interact and present synergies and trade-offs at varied spatial and temporal scales and whose management is impacted by cross sector decision-makers and stakeholders that take action at varied decision levels. Water-energy-food nexus systems are complex and dynamic systems for which the operational level cannot be overlooked to design adequate management strategies.

The novelty of this methodology lies in it being the first one to combine spatial operational multi-agent based integrated simulations of complete water-energy-food nexus systems with strategic multi-criteria decision-making methods and multi-objective optimization. The framework simulates nexus systems at temporal and spatial operational scales to derive strategic spatial allocations of resources. The framework is used to allocate land-use alternatives to parcels for agricultural territories. The number of possible combinations of land-use allocations to parcels equals the number of possible parcel land-use allocations explored for each parcel exponential the number of parcels in the territory considered. Multi-criteria decision-making methods based on exploratory Monte Carlo simulations have been designed to provide decision support for large territories (more than 1000 parcels) for which more than two land-use allocation alternatives are compared for each parcel. A multi-objective optimization method has been designed to produce optimized regional level land-use scenarios. The multi-objective optimization method is limited computationally and can face convergence issues when the number of possible combinations of land-use allocations to parcel explodes.

The methodology has been applied to an agricultural watershed of approximately 800 km² and 15224 parcels situated downstream the French Aveyron River. The watershed experiences water stress and is located in one of France's sunniest regions. Renewable energy production in agricultural land appears as a means to meet national renewable energy production targets and to move towards autonomous sustainable agricultural systems and regions. The installation of renewable energy generation units in agricultural land facing water stress is a perfect illustration of a complex water-energy-food system for which a holistic approach is required. MAELIA (modelling of socio-agro-ecological systems for landscape integrated assessment), a multi-agent based platform developed by French researches to simulate complex agro-hydrological systems, has been extended and used to simulate dynamics of water-energy-food nexus systems at operational level. Three strategic multi-criteria decision-making methods that combine Monte Carlo simulations with the Analytic Hierarchy Process method have been designed. The first one is local; it selects land-use alternatives that optimize multi-sector parcel level indicators. The other two are regional; decisions are based on regional indicators. The first regional decision-making method identifies the best uniform land-use regional scenario from those known and the second regional decision-making method explores the possible combinations of land-use allocations to parcels and selects the one that optimizes multi-sector criteria at regional level. A multi-objective optimization method that combines MILP (Mixed Integer Linear Programming) and goal programming has been implemented with IBM's ILOG CPLEX optimization studio to find parcel level land-use allocations that optimize regional multi-sector criteria.