

Simulating Renewable Energy Production Scenarios Under Water and Food Constraints

Amaya Saint-Bois^{a,*}, Marianne Boix^a, Ludovic Montastruc^a, Olivier Therond^b

^aLaboratoire de Génie Chimique, UMR 5503 CNRS, Toulouse INP, UPS, 4 Allée Emile Monso, 31432 Toulouse, France

^bUniversité de Lorraine, INRAE, LAE, F-68000 Colmar, France

amaya.saintbois@toulouse-inp.fr

Energy and agriculture are two big greenhouse gas emitters. Emissions of greenhouse gases lead to rising temperatures and originate long-term shifts in weather patterns, i.e. climate change, causing intense droughts, severe fires, rising sea levels and flooding, together with destructive storms. To reduce emissions, an energy transition from fossil fuels to renewable and low-carbon energy sources is essential, and this cannot be led without considering the deep interlinkages that exist between energy, water and food. Renewable production units can enter into competition with agriculture through land use, and both energy and agriculture are water dependent. Digital tools appear as an efficient and agile way to manage water-energy-food systems. Developing a generic digital tool that contributes to the acceleration of a sustainable energy transition is the aim of this research work. The current work is focused on extending Maelia, a spatially explicit multi-agent simulation platform for integrated assessment and modelling of socio-agro-ecological systems, that enables the simulation of fine-grained spatial and temporal land management scenarios. The platform includes agriculture and hydrology models, considers biomass production and recycling ones, and through this research work, will also integrate solar and windmill models. To make Maelia an innovative digital decision tool that deals with water-energy-food systems, data must be collected, assembled and treated with R, Python and QGIS.

1. Introduction

Today, French total agricultural land surface is superior to the one theoretically needed to feed the country's population on the national average diet (PARCEL, 2019). Installing windmills and solar panels in agricultural land can thus be among the actions taken in a context where an energy transition is required. Integrating renewable energy production units in agricultural land must consider water resource conservation and food production constraints and objectives, since installing energy production units in agricultural land limits the area dedicated to the food production. Water management problems in agricultural water-deficient basins is an age-old issue in France that has caused dire political tensions (SudOuest.fr and AFP, 2015). Irrigation directly affects the state of ground-water systems (Eaufrance, 2019), and the effect of solar panels (Tsai et al., 2019) and windmills (Guidehouse INSIGHTS, 2021) on ground-water systems must be studied. Literature shows that a Nexus approach, that considers the interdisciplinary and transdisciplinary dimensions of water-energy-food systems (WEF Nexus, 2011), is a no way around when considering complex interactions between energy, water and food resources (Giampietro, 2018).

Literature reviews have evidenced the lack of decision tools based on mathematical, programming and dynamic precise and realistic models that serve stakeholders involved in WEF systems, and help them make optimized decisions that consider operational, tactical, and strategic decision levels. Multi-agent models and stochastic programming are cited as future directions of studies for the Process System Engineering (PSE) community to correctly address these WEF systems with a Nexus approach (Peña-Torres et al., 2022). Classical PSE approaches build models that provide optimized strategic solutions, constraining tactical and operational ones. In WEF systems, operational conditions, such as meteorological conditions, are not flexible. Multi-agent models are suitable for simulating such systems. They enable leading bottom-up multi-level approaches where the operational level is taken into account from the beginning, and constrains possible tactical and strategic solutions. MAELIA (Therond et al., 2014), is an integrated assessment and modeling platform that enables fine-

scale realistic simulations of water-food scenarios, defined by water and crop management strategies, and constrained by the hydrology of the different water resources at the watershed level. The structure of the agricultural territory is described through GIS data, dynamics of the socio-agro-hydrological systems are described through coupled models of ecological systems (e.g. soil-crop and water resources), and agent (e.g. farmers, dam manager, water policy) behaviors are described through actions associated to the agents of the multi-agent architecture the modelling platform accounts with. Maelia integrates a graphical interface that allows visualizing spatiotemporal dynamics during the simulations, together with dynamic plots that show the evolution of environmental, economic, and social indicators that characterize the simulated scenarios. Maelia helps local stakeholders reach farming sustainability and water conservation objectives, by enabling them to design adapted cropping and farming systems, as well as adapted resource management strategies (Allain et al., 2018; Martin et al., 2016; Mazzega et al., 2014; Murgue et al., 2016; Tribouillois et al. 2022). The platform has been developed by researchers based in France, with whom a collaboration to integrate solar and windmill models in the platform has been agreed upon.

2. Methodological framework

The present study has designed a methodological framework to help stakeholders of water-energy-food systems make informed, sustainable and viable decisions. The framework relies on programming languages such as Python and R, on QGIS, a Geographical Information System tool, and on Maelia, which is based on GAMA Platform (2023), a spatially explicit multi-agent simulation platform. An R Shiny app has been designed to ease the data preparation step needed to run Water-Food simulations. To use Maelia as a digital decision tool, the following seven steps illustrated in Figure 1 below must be followed.

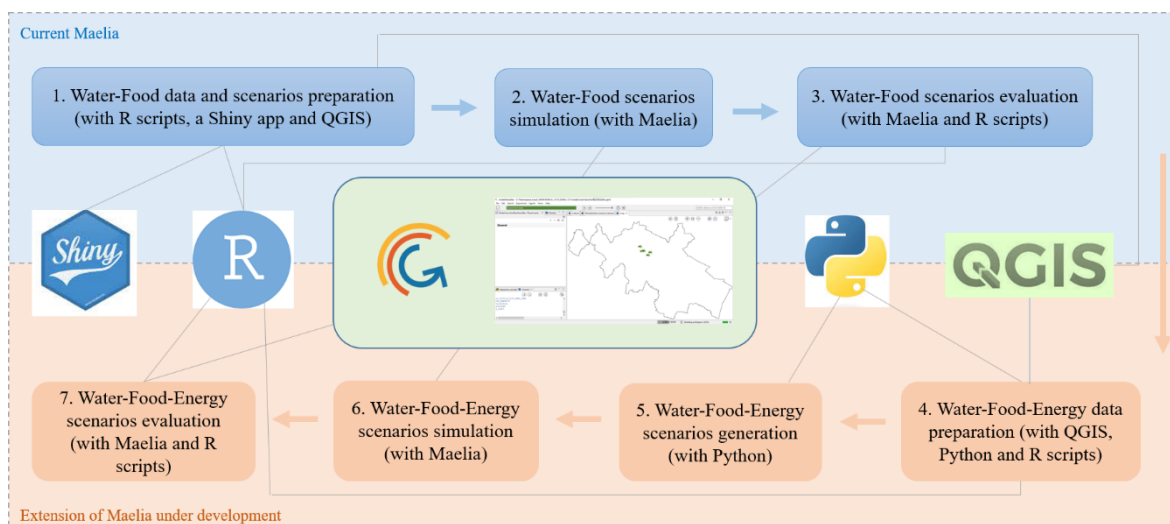


Figure 1: Methodological framework of the innovative digital decision tool

Steps 1 to 3 are already operational and have paved the way for studies such as the assessment of popular management strategies designed to solve water imbalances (Allain et al., 2018). Step 4 has been implemented recently and is presented in the following section. Step 5 to 7 are under development. The above workflow illustrates that the designed approach aims at treating water as a constraint, and acts upon food and energy components, admitting the fact that structural water management changes fall within the area of responsibility of public institutions. What makes this digital tool innovative is that the simulations that lie at the core of the approach, are: 1. done at a daily temporal and field scales, 2. consider soil and water biophysical effects and crops and energy management strategies, and 3. take into account farmers working habits, as well as, meteorological, logistic and economic operational constraints.

An inventory of all the data needed to run Water-Food simulations with Maelia can be found in Maelia (2022). Section 3 below details additional data needed to run Water-Food-Energy simulations, and an inventory of this additional data will also be given in Maelia (2022), once all the steps of the above framework are operational.

3. Water - Food - Energy data preparation

The goal of this section is to shed light on the selection of resource production and consumption, environmental, economic and social indicators that aim to characterize the state of water-food-energy systems under initial conditions of different scenarios of incorporation of renewable energy production units in existing water and agricultural land management scenarios. The indicators have been identified as relevant for enabling the comparison of different scenarios' initial states with respect to an established reference scenario. They are not intended to serve as indicators of the precise environmental, economic or social state of the systems. The objective is to use them to feed data to an algorithm that will produce optimized management solutions of different scenarios of solar panels and windmills installations in agricultural land under water constraints.

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. Selected indicators are summarized in Table 1 below:

Table 1: Multi-criteria indicators selected for a sustainable assessment of water-food-energy systems

Indicators	Energy	Water	Food
Resource production and consumption Evaluation	Annual integrated energy production, Annual electricity consumption, Energy self-sufficiency rate, Energy payback time	Total water used for irrigation, Total water released from reservoirs, Duration of river flow below low-water regulating flow (LWRF)	Annual energy and protein yields of crops, Annual food consumption, Food self-sufficiency rate, Total arable land surface
Economic Evaluation	Time it takes to reach a positive return on investment, Net present value, Internal rate of return	Water costs (irrigation costs and taxes)	Gross Margin
Environmental Evaluation	Single score - LCA with EF.3.0 (Environmental Footprint) method	Wasted rain water	Single score - LCA with EF.3.0 (Environmental Footprint) method
Social Evaluation	Farmer working hours spent at producing renewable energy	Farmer working hours spent at irrigating crops	Farmer working hours spent for all technical operations other than irrigation

3.1 Resource production and consumption evaluation

Energy production and consumption: The aim of the selected indicators regarding energy is to estimate the territorial degree of energy autonomy under different scenarios of renewable energy production in agricultural land. To estimate the energy self-sufficiency rate for each scenario, the following indicators are computed for every field of the case study:

- Potential production of solar and wind energy based on climate daily data produced by Météo France for spatial polygons of 8km*8km surfaces (Tribouillois et al., 2022).
- Mean electricity consumption of the territorial population estimated across all sectors with national open data produced by the French national operators of the electricity transport and distribution systems (Agence ORE & Gestionnaires de réseaux électricité et gaz, 2022).

Note that the compliance of land characteristics and security distances with road, rail and air routes with national regulations on solar panels and windmills installation are checked for fields to be considered as eligible for production of renewable energy. Energy payback time of solar panels and windmills is a sustainability indicator of the simulated scenarios, since energy payback time must remain small compared to the solar panels and windmills lifespan.

Water production and consumption: The aim of the selected indicators is to estimate water withdrawals and compliance with water management national regulations under different scenarios of renewable energy production in agricultural land. To estimate these, the following indicators are evaluated through Maelia's Water-Food simulations for each field of the case study land, at every time step:

- Total volumes of water used for irrigation.
- Total volumes of water released from reservoirs.
- Total duration of river flow below LWRF (low-water regulating flow).

The first indicator above illustrates the crop management strategies' degrees of water dependency, and the potential synergies between renewable energy production and limiting water withdrawals for irrigation. The second indicator measures the desirability of the scenarios, since the higher the volumes of water released from reservoirs to supply river flows, the less desirable are the scenarios, since these water releases have an economic cost, and indicate a water deficient situation. The third indicator is based on a threshold established by the European Parliament to ensure water sustainability (The European Parliament and the Council of the European Union, 2000).

Food production and consumption: The aim of the selected indicators is to estimate the territorial degree of food autonomy under different scenarios of renewable energy production, i.e. the total agricultural production in terms of energy (kcal) and protein of the simulated scenarios compared to the one needed to achieve a food self-sufficient territory. The following indicators are computed to estimate the food self-sufficiency rate for each scenario:

- Total crops' energy and protein yields estimated with Maelia's Water-Food simulations.
- Mean food consumption of the territorial population estimated with national open datasets (Agence nationale de sécurité sanitaire, de l'alimentation, de l'environnement et du travail (Anses), 2021).

Additionally, the ratio of the total arable land surface of different WEF scenarios with respect to the total agricultural land theoretically needed to achieve a food self-sufficiency territory (PARCEL, 2019) can constitute a measure in favour or against the installation of renewable energy production units in arable land.

3.2 Economic evaluation

Energy economic evaluation: The aim of the selected indicators is to estimate the economic viability of different scenarios of renewable energy production in agricultural land. The comparison of the time it takes for solar panels and windmills to generate economic benefits higher than their investment and operating costs, to their lifespan time, indicates whether they are economically profitable. Mean national investment and operating costs are considered. Evaluating the net present value and the internal rate of return of the different scenarios, enables comparison of profitability and desirability of different scenarios.

Water and food economic evaluation: Based on outputs of Water-Food scenarios simulations, Maelia enables the computation of gross margins per field, under different WEF scenarios, that consider water and crops' management strategies costs and benefits simultaneously. The platform's website gives details on formulas and data used for these computations (Maelia, 2016).

3.3 Environmental evaluation

Energy and food environmental evaluation: The environmental impact of energy production units and crops in arable land under different WEF scenarios is evaluated in comparison with an initial reference situation. End scores resulting from all impact and damage life cycle assessments (LCA) midpoint and endpoint categories derived from LCA studies undertaken with an Environmental Footprint method (European Commission, 2022), and cataloged in well-known LCA databases: Ecoinvent (Ecoinvent, 2013) for energy production units and Agribalyse (Agribalyse, 2022) for crops, are considered. Figure 2 below illustrates the approach.

A final crop environmental impact score and a final energy environmental impact score are computed for each scenario by doing the sum of the impacts of the crops, respectively the energy units, added to the simulated scenario with respect to the reference scenario, minus the sum of the impacts of the crops, respectively the energy units, removed in the simulated scenario with respect to the reference scenario.

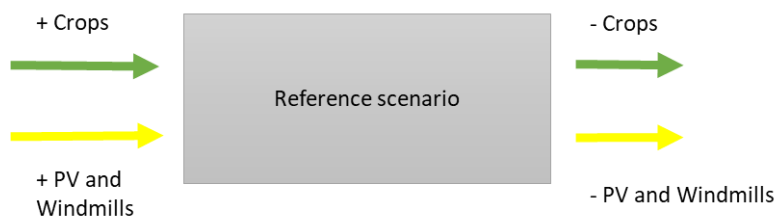


Figure 2: Illustration of the energy and food environmental evaluation approach

Water environmental evaluation: To evaluate sustainability of the WEF scenarios from an environmental point of view with respect to water, the annual efficiency of rain water is estimated for each scenario. Maelia enables the computation of this indicator by estimating the total water withdrawn from all water resources (hill reservoirs, water tables and rivers) for irrigation.

3.4 Social evaluation

As a first indicator of social sustainability of the WEF scenarios, the total farmer's working hours spent at irrigation, and the total farmer's working hours spent for all the other technical operations involved in crop management techniques are evaluated by Maelia. The total farmer's working hours spent producing renewable energy is considered null, since the installation and maintenance of renewable energy units is ensured by external experts.

4. Conclusions

To sum up, the aim of this research is to develop a state-of-the-art digital decision tool for stakeholders of the WEF nexus intervening at all operational, tactical, and strategic levels, by extending Maelia, a spatially explicit multi-agent simulation platform for integrated assessment of socio-agro-ecological systems. This new version of the MAELIA platform is a novelty due to: (i) the precise and realistic biophysical models it integrates, (ii) its bottom-up approach; its multi-agent architecture considers operational constraints at daily time steps and field levels, at the same time it considers tactical and strategic constraints, and (iii) its ability to model a large panel of scenarios in varied territories with different local characteristics.

At the writing time of this article, the data collection, analysis, and selection of multi-criteria indicators needed to feed algorithms that will generate optimized WEF scenarios have been completed. As soon as all the steps of the presented methodological framework are undertaken and become operational, Maelia will be able to simulate renewable energy production scenarios under water and food constraints. This tool will come as a guide for stakeholders that wish to contribute to a sustainable and resilient energy transition considering water resource conservation and food production objectives. It will inform them about the economic, environmental, and social benefits and drawbacks of different scenarios of integration of renewable energy production units in local agricultural lands. The tool will first be tested on French Aveyron's river basin territory, but it can be applied to all agricultural landscapes for which a Land Parcel Identification System is available and for which specific agricultural characterization data of cultivated crops, as well as meteorological data, can be made available. A sensitivity analysis on the number of energy units installed in agricultural land will be performed in order to characterize extreme scenarios and identify major risks.

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