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A water-energy-food security nexus framework based on optimal resource allocation

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ABSTRACT

Urbanization, increasing demands, and climate change are critical challenges to ensure water, energy, and food security. The water-energy-food nexus requires integrating tools to guide the allocation of resources and promote sustainability. This work presents a mathematical formulation for the optimal design and management of resources to enhance the water-energy-food nexus security. Resource security is measured through indicators related to the availability, access, and sufficiency of water, energy, and food. Furthermore, the problem was analyzed under different allocation schemes (social welfare, Rawlsian, Nash, and Rawlsian-Nash) to maximize the global resource security (including water, energy, and food) and obtain the optimal design of the system. Therefore, the water, energy, and food security indices are considered as the objectives of interest. To show the applicability of the model, a Mexican state evaluated by regions was selected as a case study. Results show that through this approach, the security of the water, energy, and food sectors could be increased 6%, 56%, and 26%, respectively, and 27% the security of the water-energy-food nexus using the social welfare scheme in the addressed case study. The proposed water-energy-food nexus framework can be applied to any region with the corresponding data.

1. Introduction

Water, energy, and food are essential resources for meeting basic human needs and economic development (FAO, 2014). The water-energy-food (WEF) nexus introduced in the Bonn Conference (Hoff, 2011) has become a relevant topic improving synergies in the water, energy, and food sectors and achieving sustainable development by promoting resource security. The study of the WEF nexus is useful to identify trade-offs between resources and is important for the development of methods towards the sustainable integration of resources and the creation of policies that guide the decision-making of social planners and governments to achieve security of resources (Li and Ma, 2020).

Water-energy-food security refers to the access to sufficient and safe water, energy, and food. In recent years, the security of these three connected resources has been widely studied (Cansino-Loeza et al., 2020; Mohammadpour et al., 2019; Pahl-Wostl, 2019; Romero-Lankao et al., 2018), and researchers have discussed and proposed strategies and policies for the improvement of resource management (Anser et al., 2020; Kaddoura and El Khatib, 2017; Kurian, 2017; Smith et al., 2020). Due to the multidimensional nature of the WEF nexus, decision-making methods have been used to address the challenges that the nexus faces, and numerous studies have centered mainly on the performance of one or two sectors (Fernández-Ríos et al., 2021; Zhou et al., 2019). Furthermore, new approaches have been extensively proposed to enhance the synergies between resources and face climate change events and globalization using quantitative analysis methods (Radini et al., 2021; Yue et al., 2021; Zhang et al., 2018). In this context, optimization models have been proposed for the sustainable design for resource management (González-Bravo et al., 2018; Ogbolumani and Nwulu, 2021), the planning of the WEF nexus involving multiple objectives in conflict (Cansino-Loeza and Ponce-Ortega, 2021; Chamas et al., 2021) or under uncertainty (Ma et al., 2021; Yu et al., 2020), and the performance of the WEF nexus when policies are incorporated (Golfam et al., 2021; Mroue et al., 2019; Sušnik et al., 2021). There is vast research on the optimization of the WEF nexus, it has been modeled under different spatial and temporal scales considering different stakeholders. In addition, different methods have been applied to analyze the interactions between resources such as input-output models, dynamic systems models, life cycle assessment, and stochastic optimization. The design of the systems has been guided mainly by the optimization of the total

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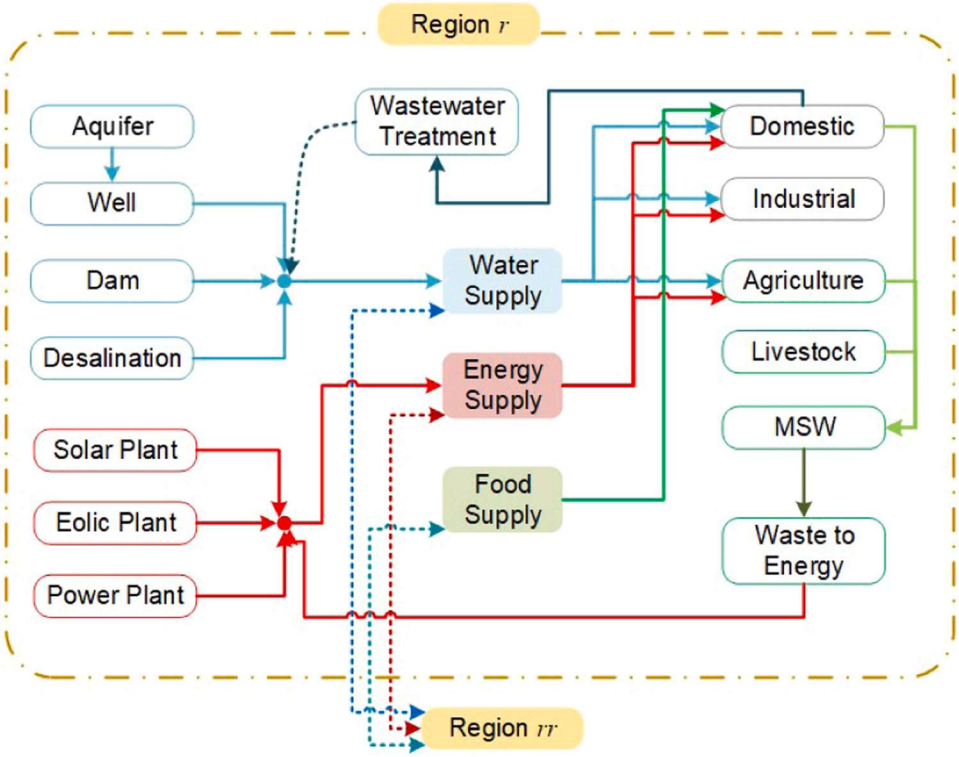

Fig. 1. General Superstructure.

annual cost, land use, water consumption, and greenhouse gas emissions (GHGE). However, despite the progress made towards the WEF nexus, there is still a relative lack of methods that allow quantifying, optimizing, and evaluating the nexus security in the planning and design of a WEF system.

It has been highlighted that a driving factor to achieve long-term sustainability is the security of the WEF nexus, and its improvement implies optimal planning and resource management policies, as well as a proper allocation or distribution of resources. The allocation of resources is one of the main concerns in social planning. The concept of the allocation scheme was originally developed through a social perspective to measure the welfare of society. Typically, when optimization models are solved, the allocation of resources is guided by the maximization of the sum of the players' utilities or the objectives in interest, this is known as the utilitarian approach or social welfare. However, according to its axiomatic properties, solving problems based on this approach may lead to non-unique solutions since different allocations of resources can give the same total utility of the system. Furthermore, the social welfare function may not properly capture the scales or sizes of the objectives/indices of interest due to their affine nature. Therefore, it may favor large objectives/indices of interest and lead to inequalities among them. The affine invariance property states that an allocation or solution under scaling of the objectives of interest is equal to the affine transformation of the solution obtained under the original system. This ensures that the allocation is scale-invariant. However, some schemes may present weak affine invariance and there is no guarantee that the solution for the transformed system is the same as in the original system(Sampat and Zavala, 2019). As an alternative to this approach, different allocation or distribution schemes have been reported and have been associated with fairness measures to avoid the inequalities between objectives/indices of interest. For instance, in the Rawlsian scheme proposed by Rawls (Rawls, 1971), the allocation of the least advantaged objective to evaluate is maximized. However, this approach can also lead to non-unique solutions. Also, it does not capture scales properly and large objectives may be ignored. On the other hand, Nash (Nash, 1950) proposed an allocation scheme that maximizes the product of the allocations which is equivalent to maximizing the sum of the logarithms of the allocations. This formulation captures the system scales naturally and gives unique solutions. Using these distribution schemes allows to solve the problem through different perspectives and to find solutions that capture the scales of the objectives of interest. In this context, allocation schemes have been addressed in water distribution networks for agriculture (Munguía-López et al., 2019), eco-industrial parks (Cruz-Avilés et al., 2021), residential complexes (Munguía-López et al., 2020), and fuel production systems (Munguía-López et al., 2021).

Nonetheless, fairness measures related to allocation schemes in integrated WEF systems have not been addressed and their implementation has to be recognized as useful tools to guide the decision-making of social planners and governments for an efficient and fair system design that could bring environmental and social benefits. Therefore, the novelty of this work is the development of a model formulation for the integration of the WEF nexus involving indicators to measure the WEF security nexus, where the optimal distribution of resources is evaluated through different allocation schemes. Since the nexus is made up of three interconnected sectors, improving security in one of these sectors could result in an improvement of the nexus. With traditional allocation schemes such as the social welfare approach, the model would seek to maximize the sector that could cause a greater contribution to maximize the nexus (Bertsimas et al., 2011). However, when using other schemes such as the Rawlsian allocation (Rawls, 1971), the sector that has the lowest level of security could be maximized. On the other hand, the three sectors could be maximized simultaneously as much as possible through the Nash scheme (Nash, 1950). Therefore, in this work, we evaluate different resource allocation schemes to maximize the security of the water-energy-food nexus.

2. Problem statement

The macroscopic water-energy-food nexus integration for a set of regions in a given state is addressed as follows:

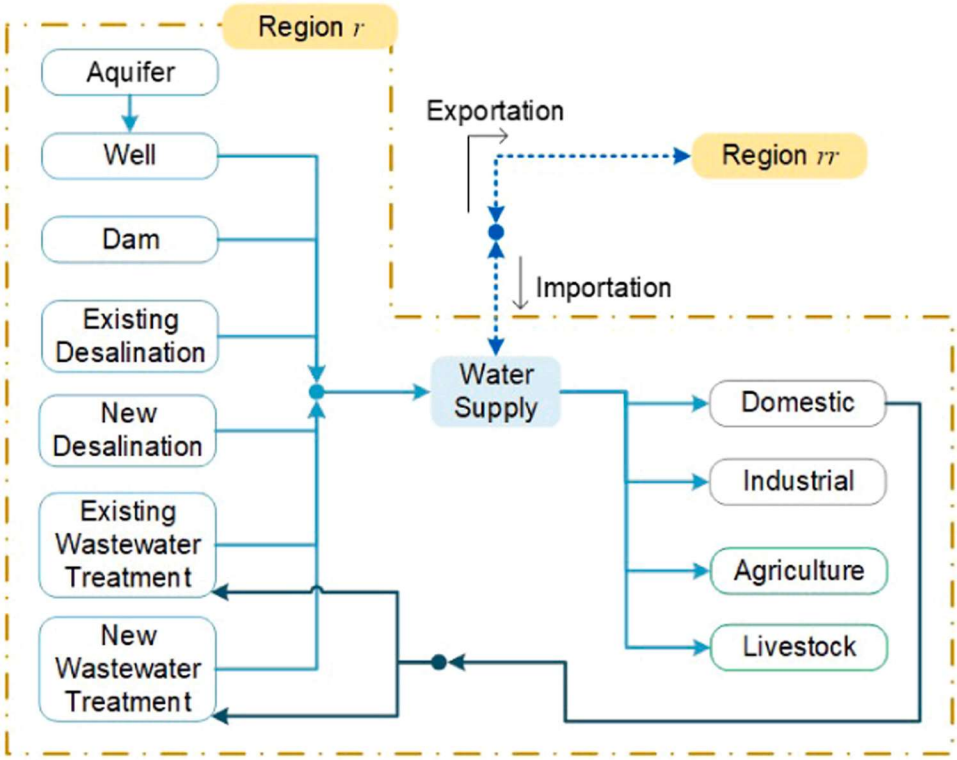

Fig. 2. Water sector superstructure.

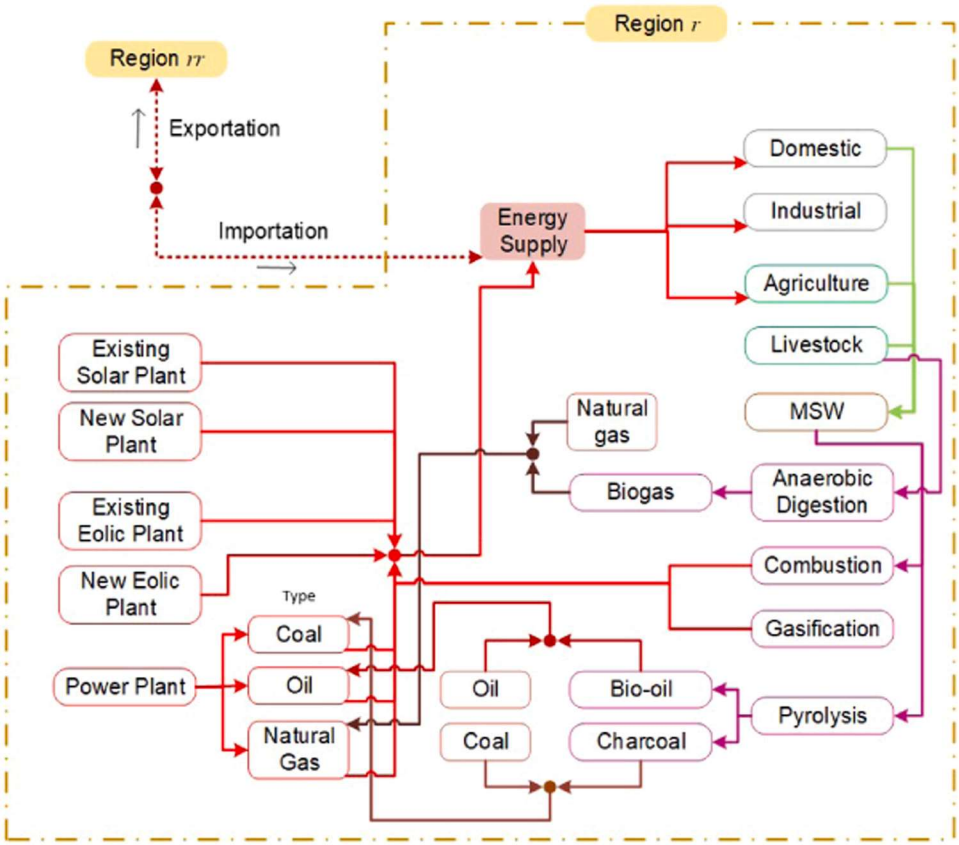

Fig. 3. Energy sector superstructure.

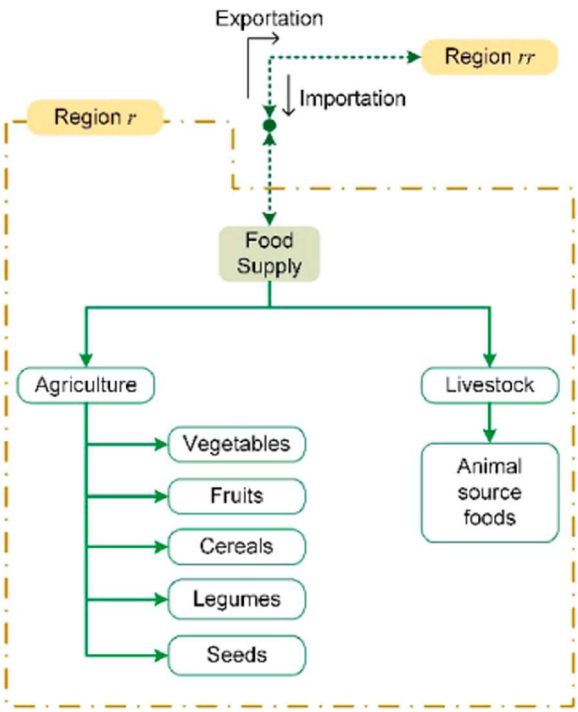

Fig. 4. Food sector superstructure.

Table 1
Nutritional information of different types of food (Health Secretary, 2010).

	Calories (kcal)	Protein (g)	Carbs (g)	Fats (g)	Servings per day Min	Servings per day Max
Vegetable	25	2	4	0	3	5
Fruit	60	0	15	0	2	4
Grain	70	2	15	0	6	11
Dairy	95	9	12	2	1	2
Meat	40	7	0	1	2	3
Legumes	120	8	20	1	2	3
Seeds	70	3	3	5	0	2

- Water, energy (electricity), and food demands for domestic, industrial, agriculture, and livestock activities are considered.
- Demands are determined by the population of the region that has access to water, electricity, and food.
- Water demand can be satisfied by wells, dams, reclaimed water, and water from desalination plants (see Fig. 2).
- Electricity demands can be satisfied by existing power plants, solar and wind parks, and biomass energy (see Fig. 3).
- Energy requirements for power plants can be satisfied using fossil fuels or biofuels.
- Food demand is covered by agricultural and livestock production (see Fig. 4).
- Food production is determined by the minimum macro-nutrients required for the population.
- Municipal solid wastes are treated in Waste-to-Energy technologies (WtE) (i.e., anaerobic digestion, incineration, pyrolysis, and gasification) for the conversion of biomass into biofuels to cover the electricity requirements in the region. The amount of municipal solid waste per capita per year was multiplied by the number of inhabitants of the region to calculate the amount of municipal solid waste generated per year.

The problem consists in determining the optimal water, energy, and food distribution in the region accounting for economic, environmental, and social objectives. The model seeks to optimize the security of the WEF by the evaluation of the water, electricity, and food availability, accessibility, and sufficiency. The model is represented in the superstructure (see Fig. 1) that indicates all the possible alternatives to solve the problem. In addition, it is proposed to evaluate different allocation schemes to address the distribution of resources.

3. Water-energy-food nexus optimization framework

Following the problem statement, the mathematical model was developed based on the superstructure presented in Fig. 1. It is important to mention that modelling all the WEF interactions leads to a complex mathematical optimization problem. However, this study is focused on the distribution of resources to maximize the security of the WEF nexus in a macroscopic system through different allocation schemes. The mathematical model is presented in detail in the supplementary material of this article, it consists of mass balances regarding water, electricity and different types of food, operating restrictions to determine the existence of new technologies for its implementation, annualized capital cost and operating cost of the technologies, and emissions associated to the operation of WtE and wastewater treatment plants, fuels and food production. The mathematical model is formulated to explore the security of the resource in different regions, and it considers the import/export of water, energy and food between the regions addressed which are called internal import/export, and also import/export resources can be given from other regions from the rest of the world named external import/export.

The water sector considers the production of water from groundwater and surface water sources, water from desalination systems and reclaimed water. In this case, existing and new desalination plants and wastewater treatment plants to meet the water demand are considered (Fig. 2). As can be seen, the mathematical model is formulated considering different alternatives for the integration of resources; however, some alternatives can be removed according to the case study evaluated. For instance, if a region does not have territory connected to an ocean, the desalination plant is not considered in the model. For the energy sector, electricity was the main type of energy involved in the model and it was the only type of energy to quantify the security of the sector. An important limitation of the model is that transportation energy demand towards food distribution was not included in the model. Fig. 3 shows the technologies considered for the formulation model; energy can be produced from conventional and renewable energy processes. On the other hand, WtE for the treatment of msw are involved to produce biofuels that can help to satisfy the energy requirements in the power plants. Finally, the food sector was formulated considering the food production from agriculture and livestock to meet the food demand of population (Fig. 4). In many countries, food consumption patterns are very far from healthy eating habits. However, if the goal of a country is to improve the food security of the population, it must ensure the availability of different types of food. According to the WHO (WHO, 2021), a healthy diet is essential for good nutrition and health, and it comprises a combination of different foods such as cereals, legumes, fruits, vegetables, and food from animal sources. Therefore, considering the food security concept, the food production is modeled based on the serving per day of the different groups of food (cereals, legumes, fruits, vegetables, and food from animal sources) that a person must have. The maximum and minimum servings per day account for the macronutrients that a person needs to intake for good nutrition (Table 1).

This way, it can be quantified how much food is produced for covering the access to people assuming that the servings per day of different groups of food are based on a healthy diet. Food production of the different types can be less or more than the required for a healthy diet, however, the model seeks to determine the optimal production of food to attend to the nutritional requirements. Human behavior is so complex and people cannot be forced to follow a healthy diet, but at least there has to be enough food to provide a balanced diet. On the

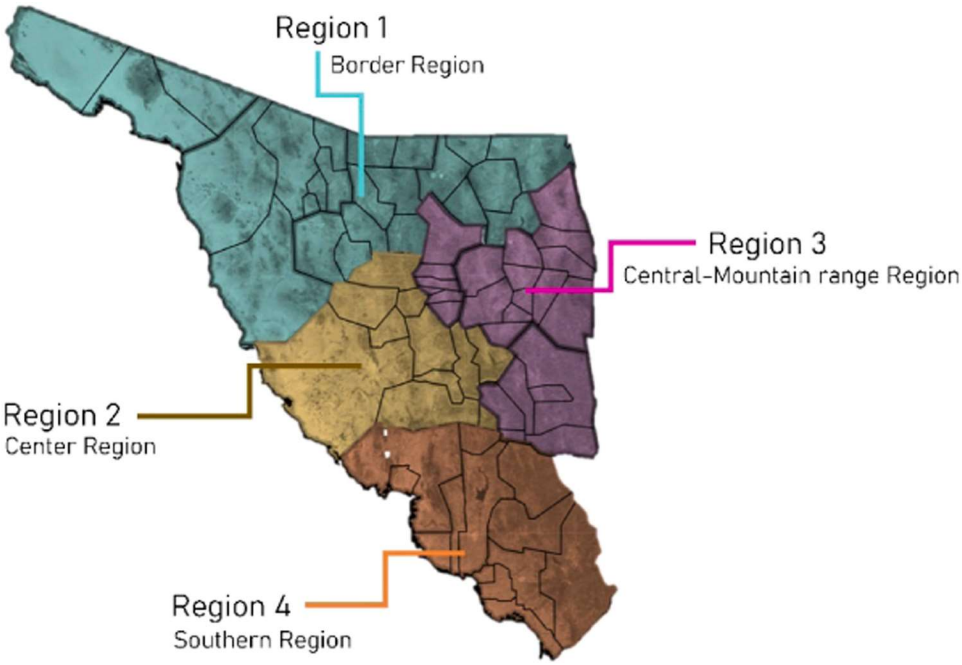

Fig. 5. Case Study representation.

Table 2
Current water-energy-food nexus security indices.

	Water			Energy			Food
	$I^W_{Availability}$	$I^W_{Accessibility}$	$I^W_{Sufficiency}$	$I^E_{Availability}$	$I^E_{Accessibility}$	$I^E_{Sufficiency}$	$I^F_{Accessibility}$
R1	0.666	0.981	0.666	0.395	0.988	0.395	0.751
R2	2.127	0.991	1.000	1.377	0.978	1.377	0.751
R3	0.195	0.971	0.195	1.036	0.980	0.141	0.751
R4	1.007	0.958	1.007	0.224	0.970	0.215	0.751

Table 3
Economic and environmental aspects of the allocation schemes.

	Social welfare	Rawlsian	Nash	Rawlsian-Nash
WATER (hm^3)	6135.56	6135.56	5363.63	5363.35
COST (MMUSD)	1913.64	1699.77	1660.53	1141.26
GHGE (Ton CO_2)	12,332.00	9603.00	9753.00	9923.00

Table 4
WEF Security Index for the schemes analyzed.

	Social welfare	Rawlsian	Nash	Rawlsian-Nash
I^{water}	0.953	0.953	0.849	0.834
I^{energy}	1.182	0.953	0.93	0.91
I^{food}	2.105	1.495	1.547	1.299
I^{WEF}	1.413	1.134	1.109	1.014
Water				
$I^W_{Availability}$	1.086	1.086	0.774	0.777
$I^W_{Accessibility}$	1	1	1	0.95
$I^W_{Sufficiency}$	0.774	0.774	0.774	0.777
Energy				
$I^E_{Availability}$	1.390	1.048	1.012	0.964
$I^E_{Accessibility}$	0.988	0.988	0.988	1
$I^E_{Sufficiency}$	1.168	0.825	0.79	0.764
Food				
$I^F_{Availability}$	4.631	2.969	3.3	2.375
$I^F_{Accessibility}$	1	0.951	0.988	0.951
$I^F_{Sufficiency}$	0.685	0.564	0.354	0.57

other hand, in this work, it was assumed that the population follows an omnivorous diet because most of the population does, however, there can be added restrictions to the model to evaluate the impact of having a vegan or vegetables-only diet. Nevertheless, studies regarding water consumption in omnivorous, vegetarian, and vegan diets have shown major water savings in vegetarian and vegan diets (Zucchinelli et al., 2021). For instance, a survival diet would require 1 m^3 of water per day per capita, whereas a diet mostly made with animal products needs some 10 m^3 per day per capita.

3.1. WEF Nexus Security Index

Water, energy, and food are major resources to sustain life; nowadays, the development of strategies to support the decision-making in the planning of water-energy-food nexus systems are needed and will help to decrease resource insecurity. Security of resources is a wide concept that can be addressed from different perspectives. Water security is a fundamental goal defined as the capacity to safeguard the availability of water, and the access to adequate and affordable clean water in a sustainable way (Zakeri et al., 2022). Energy security includes providing affordable, efficient, socially, and environmentally friendly energy supplies (Brodny and Tutak, 2021). Food security exists when all people, have physical, social, and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life at all times (FAO, 2020). Water-energy-food nexus security is a complex concept and covers all its possible dimensions would result in broad definitions, therefore, in this work we propose to evaluate the security of the water, energy, and food sectors

Table 5
WEF Security Index per region for the different schemes analyzed.

	Water			Energy			Food		
	$I^{availability}$	$I^{accessibility}$	$I^{sufficiency}$	$I^{availability}$	$I^{accessibility}$	$I^{sufficiency}$	$I^{availability}$	$I^{accessibility}$	$I^{sufficiency}$
SW									
R1	0.823 (+24%)	1.000 (+2%)	0.823 (+24%)	0.689 (+74%)	1.000 (+1%)	0.689 (+74%)	4.098	1.000 (+33%)	0.535
R2	2.249 (+6%)	1.000(+1%)	1.000 (+0%)	3.318 (+241%)	0.950 (−3%)	3.318 (+241%)	4.806	1.000 (+33%)	0.777
R3	0.282 (+45%)	1.000 (+3%)	0.282 (+45%)	1.204 (+16%)	1.000 (+2%)	0.316 (+225%)	8.735	1.000 (+33%)	0.694
R4	0.990 (−2%)	1.000 (+4%)	0.990 (−2%)	0.347 (+55%)	1.000 (+3%)	0.347 (+61%)	0.886	1.000 (+33%)	0.734
RW									
R1	0.824 (+24%)	1.000 (+2%)	0.824 (+24%)	0.522 (+32%)	1.000 (+1%)	0.522 (+32%)	2.585	0.950 (+26%)	0.397
R2	2.250 (+6%)	1.000 (+1%)	1.000 (+0%)	2.266 (+65%)	0.950 (−3%)	2.266 (+65%)	3.054	0.950 (+26%)	0.515
R3	0.282 (+45%)	1.000 (+3%)	0.282 (+45%)	1.102 (+6%)	1.000 (+2%)	0.213 (+51%)	5.655	0.956 (+27%)	0.664
R4	0.990 (−2%)	1.000 (+4%)	0.990 (−2%)	0.300 (+36%)	1.000 (+3%)	0.300 (+40%)	0.580	0.950 (+26%)	0.682
N									
R1	0.823 (+24%)	1.000 (+2%)	0.823 (+24%)	0.471 (+19%)	1.000 (+1%)	0.471 (+19%)	2.607	0.975 (+30%)	0.140
R2	1.000 (−53%)	1.000 (+1%)	1.000 (+0%)	2.201 (+60%)	0.950 (−3%)	2.201 (+60%)	3.181	1.000 (+33%)	0.337
R3	0.282 (+45%)	1.000 (+3%)	0.282 (+45%)	1.101 (+6%)	1.000 (+2%)	0.213 (+51%)	6.083	1.000 (+33%)	0.394
R4	0.990 (−2%)	1.000 (+4%)	0.990 (−2%)	0.274 (+22%)	1.000 (+3%)	0.274 (+27%)	0.692	0.975 (+30%)	0.543
RW-N									
R1	0.830 (+25%)	0.950 (−3%)	0.830 (+25%)	0.442 (+12%)	1.000 (+1%)	0.442 (+12%)	2.168	0.950 (+26%)	0.397
R2	1.000 (−53%)	0.950 (−4%)	1.000 (+0%)	2.162 (+57%)	1.000 (+2%)	2.162 (+57%)	2.376	0.950 (+26%)	0.515
R3	0.283 (+45%)	0.950 (−2%)	0.283 (+45%)	1.000 (−3%)	1.000 (+2%)	0.213 (+51%)	4.389	0.950 (+26%)	0.673
R4	0.994 (−1%)	0.950 (−1%)	0.994 (−1%)	0.240 (+7%)	1.000 (+3%)	0.214 (+0%)	0.572	0.950 (+26%)	0.693

through the evaluation of the availability, accessibility, and sufficiency of resources. Availability expresses the water, energy, and food produced in a region, accessibility is defined as the percentage of inhabitants for that the water, energy, and food needs are satisfied, and sufficiency reflects the level of dependence on external sources that a region may have in order to satisfy the demands of the population. In this work, it is considered that a way to quantify the accessibility of resources could consider both the number of inhabitants of a region and their demands for resources, so that the available resources are sufficient to satisfy the demand of the population or if required, determine the amount of resource that would have to be imported to maximize the accessibility of the resources. In this way, the accessibility index together with the availability and sufficiency indices could respond to seeking the best allocation of resources that allows greater security of the nexus.

The WEF Nexus Index is a metric to assess the progress in water, energy, and food security of a region. The WEF Nexus index is composed of nine parameters, which are indicators of water, energy, and food security in a region. Water security is evaluated through three parameters: water availability ($I^W_{Availability}$), access to water ($I^W_{Accessibility}$), and water sufficiency ($I^W_{Sufficiency}$). In the case of energy, security is evaluated through energy availability ($I^E_{Availability}$), access to electricity ($I^E_{Accessibility}$), and energy sufficiency ($I^E_{Sufficiency}$). Lastly, food availability ($I^F_{Availability}$), access to food $I^F_{Accessibility}$), and food sufficiency ($I^F_{Sufficiency}$) are the parameters used to evaluate food security. All indicators are evaluated by the following relationships. The greater the index, the best performance is achieved.

3.2. Water Security

Water security is equal to the average of the availability, accessibility, and sufficiency indices:

$$I^{water} = \sum_r \left(I^W_{Availability}\right)_r + \sum_r \left(I^W_{Accessibility}\right)_r + \sum_r \left(I^W_{Sufficiency}\right)_r \tag{1}$$

Water availability is measured as the ratio between the water produced in the region (W_r^{prod}) which involves the water availability and the water produced from unconventional processes, and the water demand (W_r^{dem}):

$$\left(I^W_{Availability}\right)_r = \frac{W_r^{prod}}{W_r^{dem}} \tag{2}$$

Water accessibility is equal to the total population ($Population_r$) minus the population without access to water services ($Pop_r^{NAccessW}$) divided by the total population:

$$\left(I^W_{Accessibility}\right)_r = \frac{Population_r - Pop_r^{NAccessW}}{Population_r} \tag{3}$$

Here, the maximum population without access to water is a target set by the decision-maker. In this work, it is intended that the available water is sufficient to provide access to the largest possible part of the population. On this foundation, for energy and food accessibility, the maximum population without access to resources is a target set by the decision-maker.

Water sufficiency index is measured as the ratio between the water imported (W_r^{imp}) and the water demand.

$$\left(I^W_{Sufficiency}\right)_r = \frac{W_r^{dem} - W_r^{imp}}{W_r^{dem}} \tag{4}$$

3.3. Energy Security

Energy security is equal to the average of the availability, accessibility, and sufficiency indices considering electricity as the only type of energy involved in the model:

$$I^{energy} = \sum_r \left(I^E_{Availability}\right)_r + \sum_r \left(I^E_{Accessibility}\right)_r + \sum_r \left(I^E_{Sufficiency}\right)_r \tag{5}$$

Energy availability is equal to the ratio between the electricity generated (E_r^{prod}) and the electricity demand (E_r^{dem}):

$$\left(I^E_{Availability}\right)_r = \frac{E_r^{prod}}{E_r^{dem}} \tag{6}$$

Energy accessibility is equal to the total population minus the population without access to electricity ($Pop_r^{NAccessE}$) divided by the total population:

$$\left(I^E_{Accessibility}\right)_r = \frac{Population_r - Pop_r^{NAccessE}}{Population_r} \tag{7}$$

Energy sufficiency is measured as the ratio between the electricity generated by renewable energy and the total electricity demand:

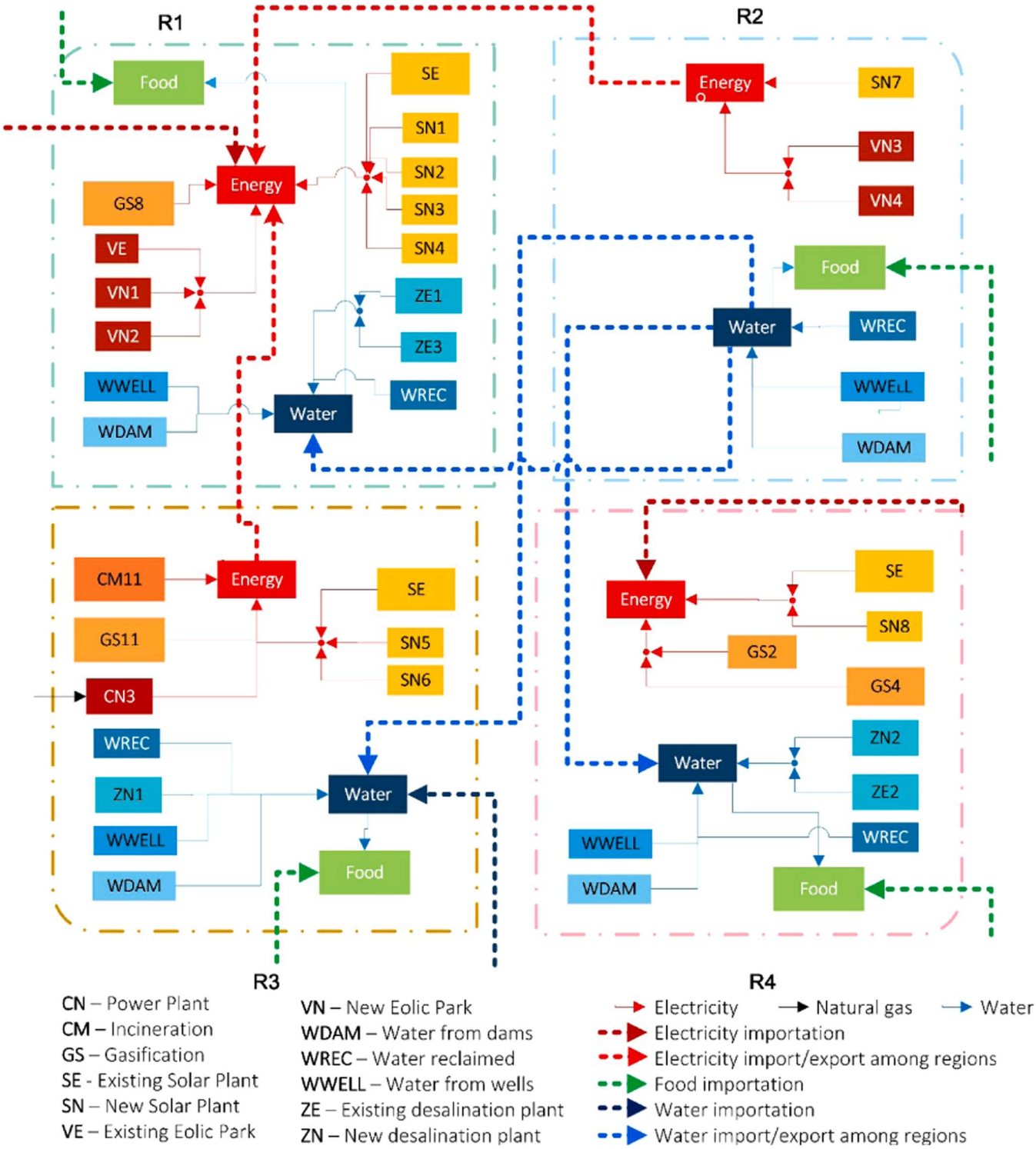

Fig. 6. Flow diagram of the social welfare scheme.

$$\left(I^{E}_{Sufficiency}\right)_r = \frac{E^{solar}_r + E^{eolic}_r + E^{biomass}_r}{E^{demand}} \tag{8}$$

3.4. Food Security

Food security is equal to the average of the food availability, accessibility and sufficiency indices:

$$I^{food} = \sum_r \left(I^{F}_{Availability}\right)_r + \sum_r \left(I^{F}_{Accessibility}\right)_r + \sum_r \left(I^{F}_{Sufficiency}\right)_r \tag{9}$$

Food availability is equal to the ratio between the food portions produced in the region ($P^{prod}_{r,fg}$) and the total portions that should be consumed for the total population ($P^{dem}_{r,fg}$):

Table 6
Emissions generated in the schemes addressed.

	GHGE x 10^3 (Ton CO_2)			
	SW	RW	RW-N	N
Sewage	0.012	0.012	0.010	0.012
Natural Gas	1.573	1.076	1.076	1.076
Municipal solid waste	0.049	0.210	0.271	0.055
Manure	1.178	1.178	1.178	1.178
Food production	4.380	4.373	4.411	4.402
Incineration	0.079	0.079	0.547	0.313
Gasification	0.660	0.660	0.313	0.539
Wastewater treatment	2.225	2.225	2.221	2.225

$$\left(I^{F}_{Availability}\right)_r = \sum_{fg} \frac{1}{fg} \cdot \left(\frac{P^{prod}_{r,fg}}{P^{dem}_{r,fg}}\right) \tag{10}$$

Food accessibility is equal to the total population minus the population without access to food ($Pop_r^{NAccessF}$) divided by the total population:

$$\left(I^{F}_{Accessibility}\right)_r = \frac{Population_r - Pop_r^{NAccessF}}{Population_r} \tag{11}$$

Food sufficiency is measured as the ratio between the portions of the food imported ($P^{imp}_{r,fg}$) and the portions of food produced ($P^{dem}_{r,fg}$):

$$\left(I^{F}_{Sufficiency}\right)_r = \sum_{fg} \frac{1}{fg} \cdot \frac{P^{dem}_{r,fg} - P^{imp}_{r,fg}}{P^{dem}_{r,fg}} \tag{12}$$

These indices can be used in the design of WEF systems and, according to the decision maker, the sectors or indices can be prioritized by assigning them the corresponding weights.

3.5. Objective functions: allocation schemes

Often, economic objectives receive more attention than environmental and social aspects in process optimization. Many works have been solved under utility maximization schemes in which individuals seek to achieve the highest level of satisfaction associated with their economic decisions. In the case of the water-energy-food nexus, not only economic factors need to be considered. New approaches are required to quantify the nexus status and identify vulnerabilities. Because of that, in this work, the water-energy-food nexus is addressed through a

Table 7
Capacity of the processes installed in the allocation schemes.

Social welfare		Rawlsian		Rawlsian-Nash		Nash	
Region.Unit	Capacity	Region.Unit	Capacity	Region.Unit	Capacity	Region.Unit	Capacity
Capacity Power Plant (MW)							
R3. CN3	477	R3. CN3	429	R3. CN3	429	R3. CN3	477
Capacity existing desalination plant (l s^{-1})							
R1. ZE1	200	R1. ZE1	200	R1. ZE1	200	R1. ZE1	200
R1. ZE3	120	R1. ZE3	120	R1. ZE3	120	R1. ZE3	120
R4. ZE2	200	R4. ZE2	200	R4. ZE2	200	R4. ZE2	200
Capacity of new desalination plant (l s^{-1})							
R3. ZN1	200	R3. ZN1	200	R3. ZN1	200	R3. ZN1	200
R4. ZN2	200	R4. ZN2	200	R4. ZN2	200	R4. ZN2	200
Capacity Incineration plant (Mton msw $year^{-1}$)							
R3. CM11	50	R3. CM11	50	R3. CM11	50	R3. CM11	50
				R4. CM2	150	R4. CM2	148.216
				R4. CM7	146.289		
Capacity eolic plant (MW)							
R1. VE1	2	R1. VE1	2	R1. VE1	2	R1. VE1	2
Capacity new elolic plant (MW)							
R1. VN1	6	R2. VN4	6				
R1. VN2	6						
R2. VN3	6						
R2. VN4	6						
Capacity gasification plant (Mton msw $year^{-1}$)							
R1. GS8	250	R1. GS9	250	R1. GS8	150	R1. GS9	250
R3. GS11	241	R3. GS10	241	R3. GS10	241	R3. GS10	241
R4. GS2	184	R4. GS2	150			R4. GS7	182
R4. GS7	150	R4. GS7	184				
Capacity solar park (MW)							
R1. SE1	110	R1. SE1	110	R1. SE1	110	R1. SE1	110
R1. SE2	99	R1. SE2	99	R1. SE2	99	R1. SE2	99
R1. SE3	180	R1. SE3	180	R1. SE3	180	R1. SE3	180
R1. SE4	137.5	R1. SE4	137.5	R1. SE4	137.5	R1. SE4	137.5
R1. SE5	100	R1. SE5	100	R1. SE5	100	R1. SE5	100
R1. SE6	125	R1. SE6	125	R1. SE6	125	R1. SE6	125
R3. SE7	125	R3. SE7	125	R3. SE7	125	R3. SE7	125
R3. SE8	100	R3. SE8	100	R3. SE8	100	R3. SE8	100
R3. SE9	21.3	R3. SE9	21.3	R3. SE9	21.3	R3. SE9	21.3
R3. SE10	25	R3. SE10	25	R3. SE10	25	R3. SE10	25
R4. SE11	99	R4. SE11	99	R4. SE11	99	R4. SE11	99
R4. SE12	200	R4. SE12	200	R4. SE12	200	R4. SE12	200
R4. SE13	90	R4. SE13	90	R4. SE13	90	R4. SE13	90
Capacity new solar park (MW)							
R1. SN1	100	R1. SN3	96				
R1. SN2	100						
R1. SN3	100						
R1. SN4	100						
R2. SN7	100						
R3. SN5	100						
R3. SN6	100						
R4. SN8	100						

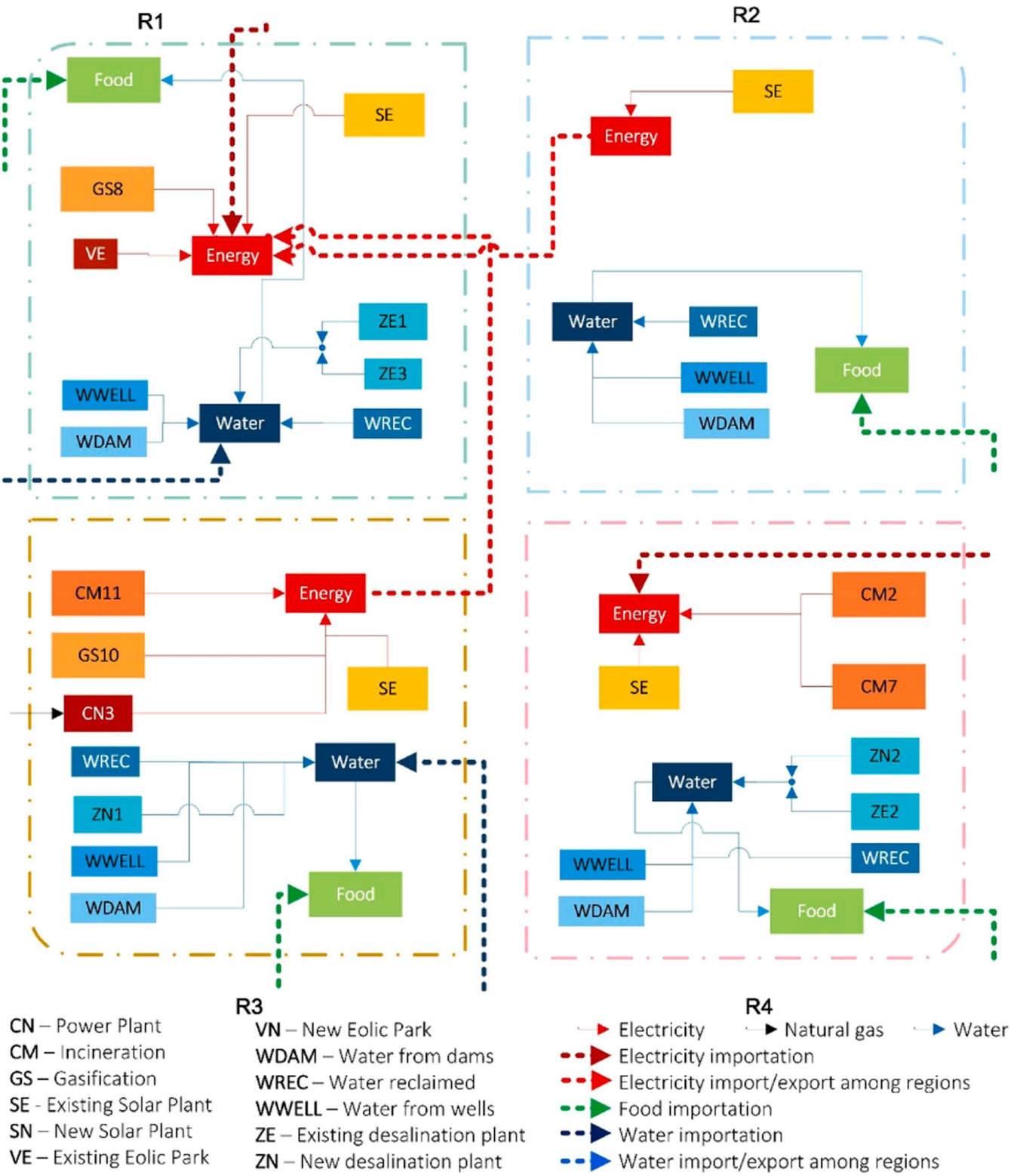

Fig. 7. Flow diagram of the Rawlsian scheme.

systematic approach that involves security indices associated with the water, energy, and food sectors. These indices can be seen as the interest of the decision makers. The proposed indices correspond to resources availability, accessibility, and sufficiency that are based on resource importation. The main objective of this work is to maximize the water-energy-food security index under different allocation schemes.

A helpful way to generate solutions that can help decision-making and address a deemed fair resource distribution is through the implementation of allocation schemes (social welfare (SW), Rawlsian (RW), Rawlsian Nash (RW-N), and Nash (N)). In this work, it is proposed to assess the allocation schemes to quantify the WEF security index. However, although these approaches have been applied to maximize economic benefits in systems, they can also be used as a multi-objective optimization tool that can be applied in different contexts, not just

Table 8
Tonnes of food demanded to cover the nutritional requirements of the population in the allocation schemes.

	SW	RW	RWN	N
Oat	25,287	21,674	21,674	21,674
Zucchini	42,942	32,730	32,730	31,572
Pumpkin	69,008	67,985	67,985	67,985
Chili	15,404	12,058	12,058	11,783
Chickpea	68,355	25,757	25,757	31,234
Corn	80,808	38,964	38,964	98,395
Melon	368,027	239,950	247,330	259,539
Potato	44,528	67,297	67,297	68,605
Cucumber	39,630	25,346	25,346	24,106
Watermelon	146,928	89,536	85,179	88,307
Tomato	9762	8640	8640	8640
Wheat	30,699	29,392	29,392	29,392
Peanut	3195	2085	2326	4684
Sorghum	59,802	56,771	56,771	33,162
Alfalfa	163,568	103,288	103,288	110,001
Asparagus	9653	9653	9653	9653
Orange	87,985	39,196	39,196	39,196
Walnut	10,479	5997	5997	10,343
Grape	21,944	19,543	19,543	19,543
Beans	75,678	107,211	107,211	117,431
Onion	78,398	3,4282	34,282	78,289
Pink Grapefruit	0	0	0	0
Apple	2220	444	444	444
Peach	6690	4617	4617	4896
Beef	22,495	11,789	11,789	12,247
Milk	236,913	154,327	154,327	188,602
Pork meat	63,417	46,068	46,068	46,850
Chicken meat	6203	6203	6203	7089
Egg	29,122	27,704	27,704	28,176

economic ones. In the case of the energy-water nexus, it could optimize the distribution of resources under objective functions that represent the social welfare, Rawlsian, Nash and Rawlsian-Nash approaches to have an efficient and equitable measurement between the energy, water, and food sectors. Therefore, the water, energy, and food security indices are the objectives of interest of the system.

The utilitarian approach known as the social welfare approach is the standard approach used in optimization processes that represent the preferences of the decision-maker. Utilitarianism holds that an action is right if it tends to produce happiness, therefore, its goal is the well-being of the entire society by maximizing the total benefit (sum of decision maker benefits). Social welfare optimization problems have been commonly used to address economic aspects. For instance, in utility maximization problems, the individual utilities are maximized over all feasible allocations that satisfy certain constraints. In this work, through the social welfare approach, the security indices associated with the water, energy and food sectors are maximized to generate the maximum benefit which is the security of the water-energy-food nexus (Eq. 13). However, multiple allocations of resources could be found since the solutions provided by this scheme may be non-unique, and thus, this method causes ambiguity.

$$\phi^{sw} = I^{water} + I^{energy} + I^{food} \tag{13}$$

The Rawlsian difference principle states roughly that inequality should be tolerated only when it makes the least advantaged better off (Hooker, 2010). The Rawlsian principle is solved through a max-min optimization problem, these means that maximizes the minimum objective (security index) for all scenarios. Therefore, the distribution of resources should maximize the security index through the maximization of the less beneficiated sector. In this work, the goal is to maximize the security index for each sector (water, energy, and food), therefore, we transform the problem including an additional variable (Θ) which now is a lower bound for each of the individual variables (indices), then the optimization problem is now a minimization problem with additional inequality constraints (Eqs. 15–17). This way, the model can maximize the least advantaged variable or index (Eq. 14).

$$\phi^{rw} = \Theta \tag{14}$$

$$-I^{water} \leq \Theta \tag{15}$$

$$-I^{energy} \leq \Theta \tag{16}$$

$$-I^{food} \leq \Theta \tag{17}$$

The mathematical expression for the Nash allocation scheme is the maximization of the geometric mean of the objectives of interest. This is equivalent to maximizing the sum of their logarithms, then, since the log function is strictly concave has a unique optimal solution which means that there are no alternative allocations that yield the same optimal solution for the Nash function (Sampat and Zavala, 2019). The Nash allocation is obtained by maximizing the sum of the logarithms of the water, energy, and food security indices.

$$\phi^{n} = \ln(I^{water}) + \ln(I^{energy}) + \ln\left(I^{food}\right) \tag{18}$$

Finally, a combination of Rawlsian-Nash schemes is included. The Rawlsian-Nash scheme was previously proposed by Munguía-Lopez et al. (2020) as a tool that combines the concepts of the Rawlsian and Nash scheme. The principle of the Rawlsian scheme is based on the fact that inequalities should be tolerated only when they are expected to benefit the disadvantaged, this means that, in the Rawlsian allocation scheme, the maximum benefit should be maximized for the least well-off target interest. On the other hand, the Nash allocation scheme maximizes the product of the objectives of interest, which is equal to maximizing the geometric mean of the objectives of interest, this is equivalent to maximizing the sum of the logarithms of the objectives, which allows capturing the system scales. An important property of this scheme is the property of symmetry which implies that there are no alternative allocations, the Nash scheme might need to sacrifice the total efficiency of the system, that is, the sum of the goals of interest to achieve fairness. Considering this, the Nash allocation scheme can be combined with the concepts of the Rawls scheme to find a solution that is both efficient and fair (Munguía-López et al., 2020). The formulation for this scheme is similar to the Rawlsian scheme because a new variable (Θ) is included and minimized. But in this case, the constraints (Eqs. 20–22) include the logarithm function, and another one is included to represent the Nash scheme (Eq. 23):

$$\phi^{rw-n} = \Theta \tag{19}$$

$$-\ln(I^{water}) \leq \Theta \tag{20}$$

$$-\ln(I^{energy}) \leq \Theta \tag{21}$$

$$-\ln\left(I^{food}\right) \leq \Theta \tag{22}$$

$$-\left(\ln(I^{water}) + \ln(I^{energy}) + \ln\left(I^{food}\right)\right) \leq \Theta \tag{23}$$

The water-energy-food nexus optimization model is solved under different cases associated with the objective functions, including the social welfare (SW), Rawlsian (RW), Rawlsian Nash (RW-N), and Nash (N) schemes in which the goal is to maximize the security of the WEF.

4. Case Study

To demonstrate the applicability of the model, the Mexican state of Sonora was selected as a case study. Sonora has been one of the most important economic entities in Mexico as it has a diversity of natural resources that facilitate the development of economic activities such as agriculture, livestock, fishing, mining, and services. Sonora is located in the northern region of Mexico, the border region (R1) of the state is covered by the Sonoran Desert, which is the hottest desert in the country. From the above, it stands out that the entity has one of the highest levels of solar irradiation at the national level (6–8 kW / h / m^2),

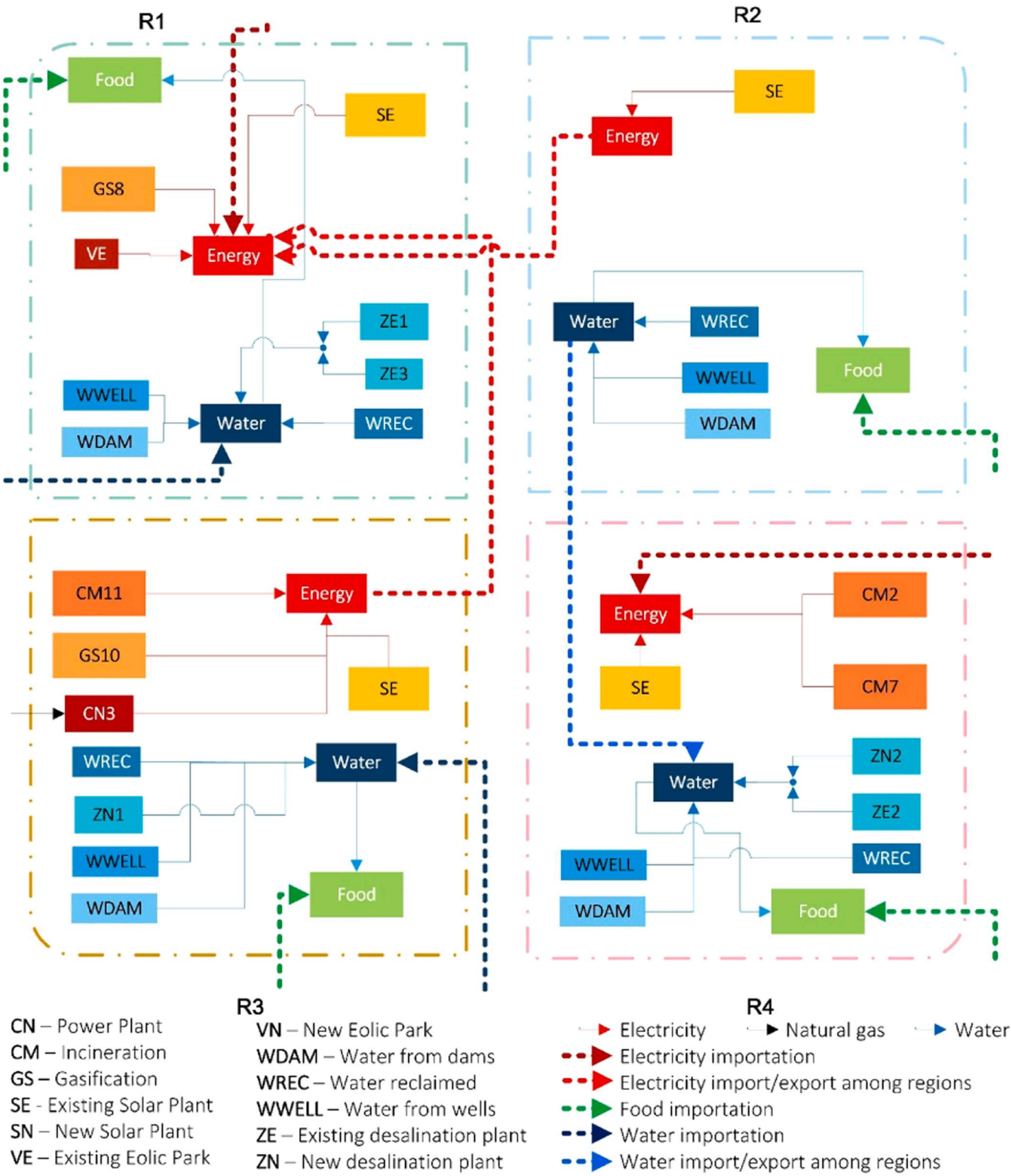

Fig. 8. Flow diagram of the Rawlsian-Nash scheme.

representing an area with high potential for the production of electricity from solar energy. On the other hand, agriculture in the state of Sonora is one of the most important economic activities. Sonora has a territorial extension of 18,484,644 ha, of which 4.1% is destined for agricultural use. Sonoran agriculture predominates in the southern region (R2), which specializes in the production of grains, oilseeds, and horticulture. However, one of the main problems of the state is that due to its geographical and hydrological conditions, providing access to water for the different economic sectors represents a great challenge. Thus, it is necessary to implement strategies to improve the agricultural development of the state. Furthermore, considering that Sonora has potential for renewable energy, the design of an integrated WEF system is addressed to increase the security of the WEF.

In this work, the Sonora state was divided into four representative

Table 9
Capital costs of the social welfare, Rawlsian, Rawlsian-Nash and Nash schemes.

Capital Cost (MMUSD) Desalination	SW	RW	RW-N	N
R1	0	0	0	0
R2	0	0	0	0
R3	5.392	5.392	5.392	5.392
R4	5.392	5.392	5.392	5.392
Wastewater treatment plants				
R1	16.947	16.947	16.947	16.947
R2	15.736	15.736	15.736	15.736
R3	8.473	8.473	8.473	8.473
R4	9.684	9.684	9.684	9.684
Eolic Park				
R1	47.02	0	0	0
R2	47.02	0	0	0
R3	0	0	0	0
R4	0	0	0	0
Solar Park				
R1	96.48	0	0	0
R2	24.12	0	0	0
R3	48.24	0	0	0
R4	24.12	0	0	0
Incineration				
R1	0	0	0	0
R2	0	0	0	0
R3	207	207	207	207
R4	0	0	414.001	201.001
Gasification				
R1	134.001	134.001	134.001	134.001
R2	0	0	0	0
R3	134.001	134.001	134.001	134.001
R4	268.002	268.002	0	134.001

regions (see Fig. 5) to evaluate the security of the WEF Nexus; The Border Region (R1), Center Region (R2), Central-Mountain range Region (R3), and Southern Region (R4). Subdivisions of the regions addressed are shown and represent the municipalities of the state, however, the analysis of the WEF nexus was addressed by region.

Table 2 presents the water, energy, and food indices associated with the availability, accessibility, and sufficiency of resources to date. Currently, the Central-Mountain range Region (R3) presents the lowest water availability while the Center region (R2) presents the highest water availability of the state; therefore, water from R2 is used to help satisfy water requirements in the near regions. On the other hand, it is shown that energy production is centered in R2, and R3 exhibits the lower energy production of the state.

The Sonora's regions present unequal distribution of resources availability and production. It can be seen that R2 presents the highest water and energy production, which is associated with its industrialized nature. On the other hand, R3 corresponds to the least urbanized region of the state, therefore, technologies for energy production are not abundant. In addition, it is important to mention that this region does not have access to the sea, and the existence of desalination plants that increase the water production in the region is not an option. According to Table 2, R2 has the highest availability, accessibility, and sufficiency indicators of the regions of the state. Nevertheless, it is important to notice that the potential of Sonora for renewable energy can be exploited, and increasing the renewable energy capacity could improve security in the energy sector. In the same way, water reuse and irrigation techniques could enhance the security of the WEF substantially.

Data associated with the model was obtained from literature and information available on federal reports. For the case study, data associated with water availability and consumption were obtained from the National Water Commission (CONAGUA), electricity data were obtained from the Federal electricity commission (CFE) and food production information was obtained from the Agri-Food and Fisheries Information Service (SIAP). We have included the data used for the case study in the supplementary material. The mathematical model proposed is formulated for a yearly time horizon because there is a lack of data regarding small temporal scales, therefore, future research should include resources production and consumption on a small-time scale.

5. Results

The mathematical formulation for the analyzed fair allocation schemes was implemented in the software GAMS. The models of the schemes correspond to a Mixed Integer Linear Programming Model (MINLP) and were solved using the solver LINDOGlobal. The social welfare is composed of 5500 constraints, 154 binary variables and 7900 continuous variables, for the Rawlsian scheme the model involves 5501 constraints, 154 binary variables and 7906 continuous variables, the Rawlsian-Nash model consists of 5500 constraints, 154 binary variables and 7906 continuous variables, the Rawlsian scheme is composed of 5501 constraints and 7905 continuous variables.

Table 3 shows the costs, freshwater consumption, and GHGE generated in the different allocation schemes. The SW scheme presents the highest costs, water abstraction and GHGE generation. On the other hand, the RW-N scheme presents the lowest cost for the system, freshwater abstraction and GHGE generation.

The results of the security index for water, energy, and food for the SW, RW, N and RW-N schemes are presented in Tables 4 and 5. It is worth mentioning that the security indices presented in Table 4 correspond to the state indices since they are the average of the security indices of the regions of the state. Therefore, some security indices are greater than 1, but it does not mean that the security of the sectors was achieved in its entirety since some indices indicate that in some regions there are more resources than those required for the population. For instance, a value greater than one for the energy availability index means that in the region more energy is produced than the energy demanded, therefore, energy could be exported to other regions. On the other hand, Table 5 shows the results of the security indicators per region and changes concerning the current situation of the case study are presented in parentheses.

5.1. Social welfare

The social welfare diagram is presented in Fig. 6. The flow diagram shows the technologies selected to cover the water and energy demands in the regions of the state. The social welfare scheme has the major renewable energy production due to the selection of new solar and eolic plants. The installation of new solar plants was determined by the model in the four regions, being region 1 (R1) the region with the highest capacity (Table 7). Different eolic parks were selected in region 1 (R1) and region 2 (R2). Due to the increase in energy production by renewable sources, the social welfare scheme presents the highest sufficiency index (1.168). On the other hand, Waste-to-energy technologies of different capacities were selected. The flow diagram shows that for R1, only gasification plants were selected, region 3 (R3) includes an incineration and a gasification plant, and in the case of region 4 (R4), two gasification plants were selected.

The results obtained in the social welfare scheme present the highest WEF Security Index (1.413) compared with the other schemes. The water, energy, and food security indices were higher than the other schemes. In the case of the water sector, the availability index was approximately 24–26% more than in other schemes, this is mainly attributed to the water production in R2, which exceeds the demand, electricity production in R2 is 3.3 times the electricity demand in the region, and it is exported to other regions to cover their electricity demands. In this scheme, although the availability of electricity exceeds the demand of the region, the model determines that electricity will be exported to other regions with low electricity production instead of providing access to all the population in R2. This is because of the principle of the allocation schemes since we want to maximize the water-energy-food nexus security of the state, therefore, the solution is guided by the maximization of resource security in the four regions

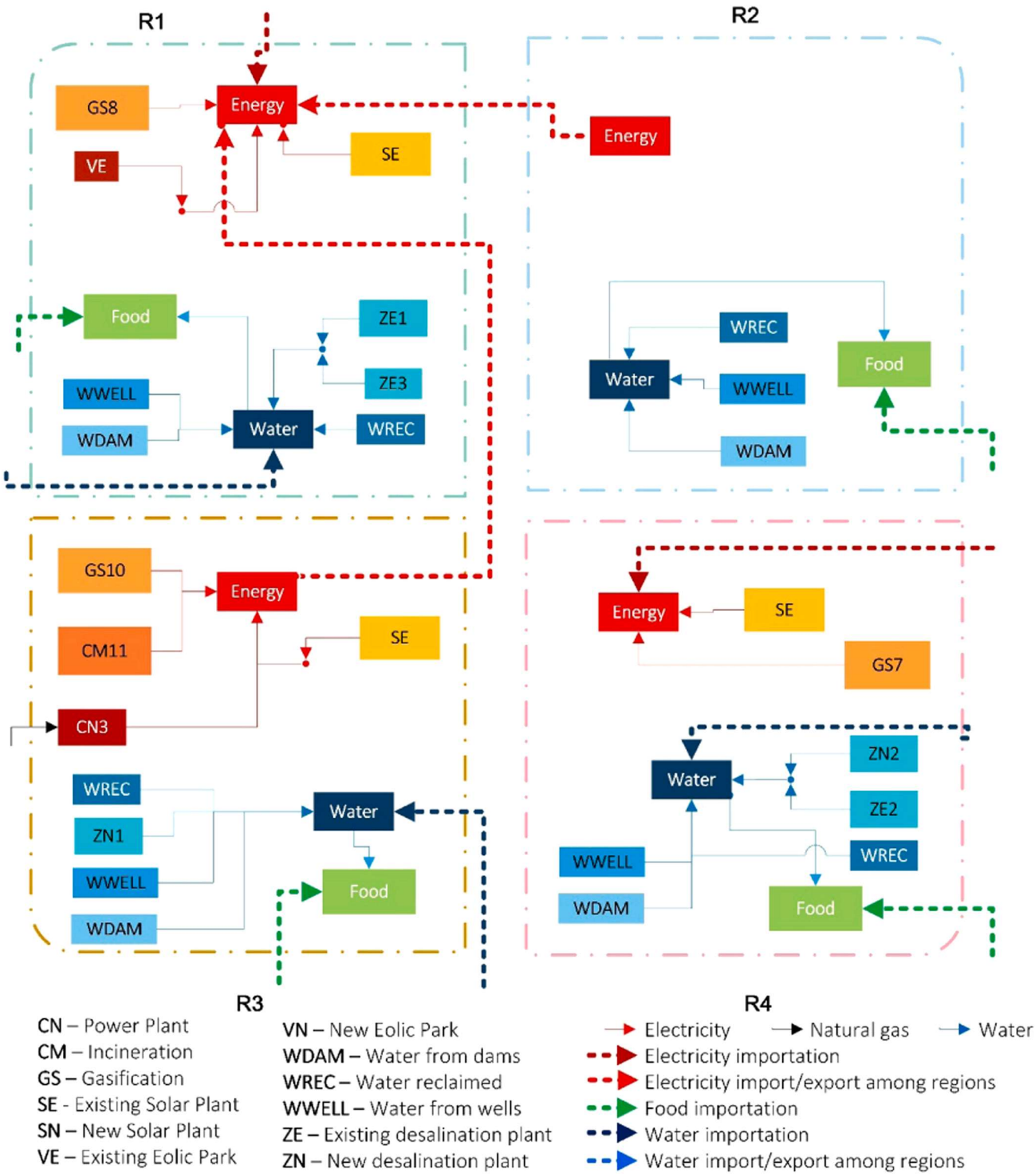

Fig. 9. Flow diagram of the Nash scheme.

seeking efficient solutions. In addition, results shows that in the case of water and food, the accessibility index is equal to 1 which means that water and food available are enough for population requirements.

The SW scheme has the major GHGE among the schemes evaluated. Food production that involves agriculture and livestock activities, is the sector with more generation of emissions, followed by the burning of natural gas to generate electricity (Table 6). On the other hand, the gasification process shows the major generation of emissions of the waste to energy technologies.

The study of the axiomatic properties of the SW allocation scheme shows that its representative function is an affine function which implies that is non-unique, from an implementation perspective, one of the

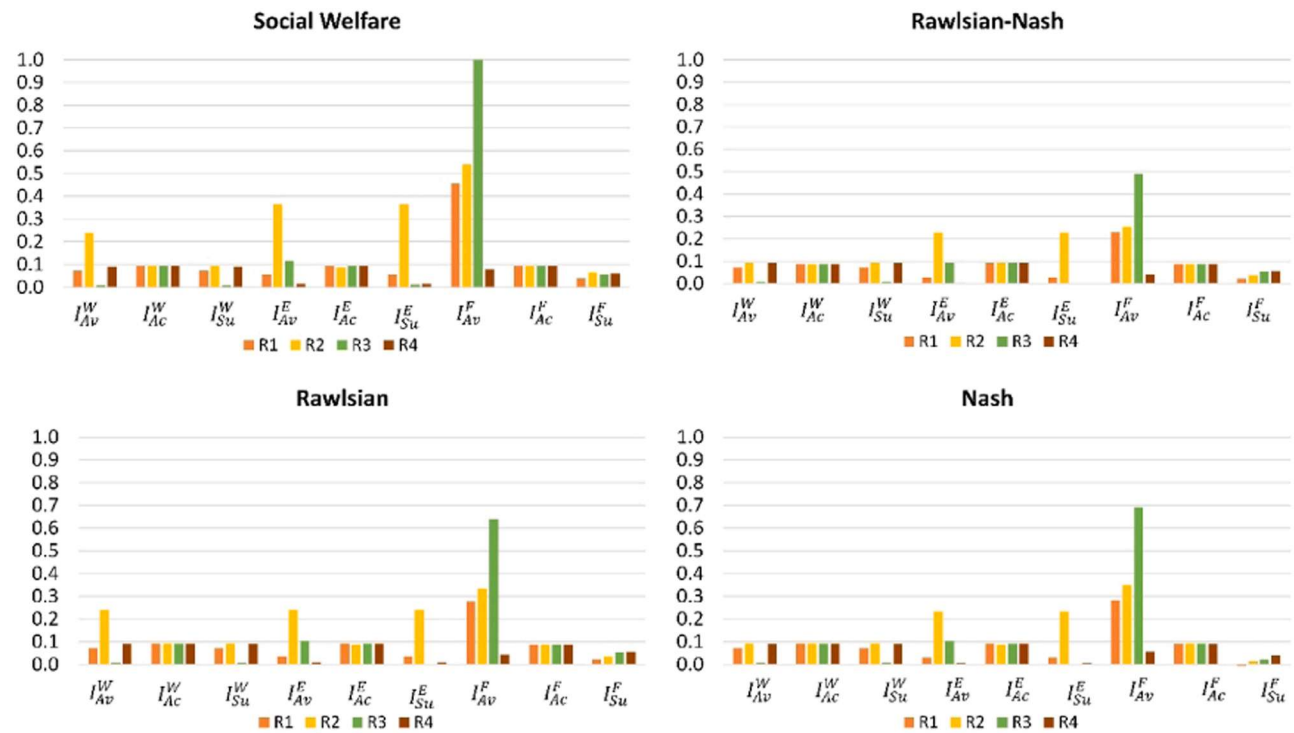

Fig. 10. Water-energy-food nexus security indices of the evaluated schemes.

disadvantages of this scheme is that it is difficult to compute all the possible solutions that can be obtained. Moreover, additional criteria may also be required to find an optimal allocation of resources (Sampat and Zavala, 2019). On the other hand, the ability to provide multiple solutions to the decision maker could be an advantage, in this sense, restrictions could be added according to the need or interest of the decision maker (i.e., costs, water consumption, and emission generation). However, from a social perspective, it should be considered that some of the solutions could be unfair, since the maximization of general welfare may imply that the good of one sector is sacrificed to serve the greater good of another sector (Stark et al., 2014).

5.2. Rawlsian schemes

The Rawlsian diagram is presented in Fig. 7. This scheme presents lower renewable energy production than the social welfare scheme, however, new solar plants were selected for all the regions, and wind energy was selected for R2, which increases the renewable energy capacity (Table 7). On the other hand, the waste-to-energy technology selected for R1 was the gasification plant, in R3 the incineration and the gasification plants were selected, and for R4 two gasification plants of different capacities were selected. The results of the system design for this scheme show a WEF security index of 1.134, which is 20% lower than the WEF security index resulting from the SW scheme because in this scheme a lower amount of resources was produced. Accessibility to water is achieved for all the population in the four regions, in the case of energy accessibility, the excess of electricity produced in R2 is sent to other regions to increase their accessibility index. In the food sector, it should be noticed that even if the availability index shows that food production is greater than the demand, not all the food produced in the region is enough to cover the nutritional requirements of the population, for this reason, some types of food need to be imported to meet the macronutrients required by the population. In the RW scheme, the accessibility index is equal to 0.95, which is 5% lower than the social welfare scheme. Table 8 shows the required food that meets the nutritional requirements for the population in the different schemes.

Results of the RW scheme do not present security indices as high as in the SW scheme, this is due to the constraints of the RW scheme in order to maximize the indices of the less disadvantaged sectors. Comparing the results obtained in the RW scheme and the current situation in Sonora, it was noted that under the RW scheme the security indices present an increase in a more balanced way, not as in the SW scheme.

5.3. Rawlsian-Nash scheme

The design for the Rawlsian-Nash scheme is composed of gasification plants selected for R1, R3 and R4, as well as the incineration plant selected in R3 (see Fig. 8). In this scheme, new solar and eolic plants were not selected by the model. This causes the energy security index to be the lowest compared to the other schemes since lower electricity is produced, especially renewable energy that causes the sufficiency energy index to decrease. Furthermore, water production in R2 is not produced in excess as in the other schemes. Water and food accessibility is covered for 95% of the population in all the regions, therefore, food demand is lower than the other schemes. Moreover, the costs of the system decreases (Table 9), this could be attributed to the fact that lower investment in the implementation of technologies is required.

The WEF security index in this scheme is the lowest of the allocation schemes addressed, it is equal to 1.014, and it is 39% lower than the WEF security index resulting from the social welfare scheme. However, it is important to mention that with the RW-N formulation a unique solution could be provided, unlike the social welfare and RW scheme. The constraints of the formulation for the RW-N scheme guide the allocation of resources to increase the security indices considering both efficiency and

fairness, which is the main attribute of this scheme. As can be seen in Fig. 9, the results of the Rawlsian-Nash scheme and the Nash scheme are similar, although they differ mainly in the food availability index, being higher in the Nash scheme.

5.4. Nash scheme

Nash flow diagram is presented in Fig. 9. In this scheme, new solar and eolic energy was not selected for the system, however, waste to energy technologies was selected; a gasification plant in R1, R3 and R4 of different capacities were included for the treatment of municipal solid wastes. In addition, an incineration plant was selected for R3. On the other hand, such as in the four schemes addressed, an existing power plant in R3 is considered which has a capacity of 3152 MW and uses natural gas as fossil fuel (376 MMcm).

For the Nash scheme, in the water sector, it is observed that R2 does not produce more water than the demand in the region, therefore, there are no internal water imports between the regions, and the water availability index is lower than the other schemes. Despite this, the water accessibility index is equal to one, which means that water production is enough to cover the water requirements of the population. On the other hand, food accessibility for all the population was not achieved in R1 and R4 and food sufficiency presents the lowest indices for the regions evaluated because it is required to import food to cover the nutritional requirements of the population. Water, energy, and food accessibility indices could be fixed to one by forcing the model to serve all people. However, due to how the indices were defined, it is possible that in the regions with enough availability of resources, the excess of resources will be exported to meet the demand of resources required to provide access to the total population in the other regions, which would tend to decrease the sufficiency index and as a consequence the WEF security index. The WEF index for the Nash scheme is equal to 1.109, with a decrease of the I^{water} and an increase of the I^{energy} compared with the current situation in Sonora. However, because of the properties of the mathematical function for the Nash scheme, results correspond to an efficient and unique. Fig. 10 shows a graphical representation of the results obtained in the optimization of the WEF security for the different allocation schemes proposed according to Table 5. Here, indices were normalized considering the food availability index in R3 as the highest value obtained (8.735) in the social welfare scheme, and the energy sufficiency index in R3 as the lowest value (0.213) in the RW scheme.

The implementation of new technologies in the WEF system will bring social benefits; however, its implementation will depend on the decision-makers such as the government that have to invest in these technologies to make a better management of resources. Furthermore, considering that through this approach the planning of the WEF nexus and distribution of resources is guided by the maximization of resources security, which involves new alternatives to increase the production of resources in a sustainable way, it is expected that for other cases, the security of the nexus will be improved because today there are different alternatives for sustainable production.

6. Conclusions

Studying the interconnections of water, energy, and food is essential for the design of systems and allocation of resources to improve the water-energy-food nexus security. This paper has presented a water-energy-food optimization framework to maximize the security of the nexus considering different allocation schemes, which support the decision-making for better management of resources and performance of the sectors. As a case study, regions of the state of Sonora from Mexico were used to implement the proposed framework. The framework was solved by considering different allocation schemes such as social welfare, Rawlsian, Nash, and Rawlsian-Nash schemes to obtain the optimal allocation of resources that maximizes the water-energy-food nexus security. By the application of the proposed approach, results show an increase in the security index of the water sector of 6%, 56% of the energy sector, and 26% of the food sector. This gives an increment of 27% in the WEF security index using the social welfare scheme, which is the highest index among the schemes evaluated. Results for the design of the social welfare scheme present the highest GHGE (12,332 ton CO_2), freshwater abstraction (6135.562 hm^3), and costs (1913.64 MMUSD) among the different allocation schemes, and a WEF security index of 1.413. Otherwise, the Rawlsian-Nash scheme presents the lowest costs ($1141.26 MMUSD), the lowest freshwater consumption (5363.35 hm^3), and the lowest WEF security index (1.014).

This work can be viewed as a step toward supporting social planners or governments making decisions using social choice functions that are automatically optimized for their needs. The addressed allocation methods can provide efficient and equitable solutions, and the selection of the allocation method for a system in any region will depend on the criterion of the decision-maker. For instance, when applying the social welfare scheme, the sum of the security indices associated with the water, energy and food sectors will be maximized to improve the nexus security index. However, multiple solutions that result in the same nexus security index could be given by this method. Furthermore, using this method could lead to inequality among the improvement of the water, energy and food sectors since it cannot capture sizes of security indicators. To overcome these limitations, the Rawlsian and Nash approaches can be used. The Rawlsian approach will be adequate if the decision-maker desires to maximize the nexus security by maximizing the security of the most vulnerable sector and will provide greater benefit to the least well-off of the sectors. On the other hand, the Nash approach will identify a unique solution where the sectors evaluated will be maximized together. Furthermore, this scheme will give a solution that captures the sizes of security indicators.

The main contribution of the proposed framework is the development of a model that provides the optimal allocation of water, energy, and food and quantifies and maximizes the security of the water, energy, and food sectors. The proposed water-energy-food nexus framework can be applied to any region at any scale with the corresponding data. Nonetheless, one of the main limitations of the model is the uncertainty related to the lack of time dimension that impacts the production and consumption of resources and the uncertainty related to the demographic changes and meteorological conditions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. WEF security index results

This appendix presents the results obtained for the schemes evaluated associated with Fig. 10.

see Table 1a.

Table 1a
WEF Security Index for the schemes analyzed.

	Social welfare	Rawlsian	Nash	Rawlsian-Nash
I^{water}	0.953	0.953	0.849	0.834
I^{energy}	1.182	0.953	0.93	0.91
I^{food}	2.105	1.495	1.547	1.299
I^{WEF}	1.413	1.134	1.109	1.014
Water				
$I^{W}_{Availability}$	1.086	1.086	0.774	0.777
$I^{W}_{Accessibility}$	1	1	1	0.95
$I^{W}_{Sufficiency}$	0.774	0.774	0.774	0.777
Energy				
$I^{E}_{Availability}$	1.39	1.048	1.012	0.964
$I^{E}_{Accessibility}$	0.988	0.988	0.988	1
$I^{E}_{Sufficiency}$	1.168	0.825	0.79	0.764
Food				
$I^{F}_{Availability}$	4.631	2.969	3.3	2.375
$I^{F}_{Accessibility}$	1	0.951	0.988	0.951
$I^{F}_{Sufficiency}$	0.685	0.564	0.354	0.57

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.03.006.

References

Anser, M.K., Yousaf, Z., Usman, B., Nassani, A.A., Qazi Abro, M.M., Zaman, K., 2020. Management of water, energy, and food resources: go for green policies. J. Clean. Prod. 251, 119662 https://doi.org/10.1016/J.JCLEPRO.2019.119662.

Bertsimas, D., Farias, V.F., Trichakis, N., 2011. The price of fairness. Oper. Res. 59 (1), 17–31. https://doi.org/10.1287/opre.1100.0865.

Brodny, J., Tutak, M., 2021. The comparative assessment of sustainable energy security in the Visegrad countries. A 10-year perspective. J. Clean. Prod. 317, 128427 https://doi.org/10.1016/J.JCLEPRO.2021.128427.

Cansino-Loeza, B., Ponce-Ortega, J.M., 2021. Sustainable assessment of water-energy-food nexus at regional level through a multi-stakeholder optimization approach. J. Clean. Prod. 290, 125194 https://doi.org/10.1016/J.JCLEPRO.2020.125194.

Cansino-Loeza, B., Sánchez-Zarco, X.G., Mora-Jacobo, E.G., Saggiante-Mauro, F.E., González-Bravo, R., Mahlknecht, J., Ponce-Ortega, J.M., 2020. Systematic approach for assessing the water–energy–food nexus for sustainable development in regions with resource scarcities. ACS Sustain. Chem. Eng. 8, 13734–13748. https://doi.org/10.1021/ACSSUSCHEMENG.0C04333.

Chamas, Z., Abou Najm, M., Al-Hindi, M., Yassine, A., Khattar, R., 2021. Sustainable resource optimization under water-energy-food-carbon nexus. J. Clean. Prod. 278, 123894 https://doi.org/10.1016/J.JCLEPRO.2020.123894.

Cruz-Avilés, D.J., Munguía-López, A., del, C., Ponce-Ortega, J.M., 2021. Optimal design of water networks in eco-industrial parks incorporating a fairness approach. Ind. Eng. Chem. Res. 60, 8844–8860. https://doi.org/10.1021/ACS.IECR.1C00197.

FAO, 2014. The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture. URL http://www.fao.org/3/a-bl496e.pdf (Accessed 5 July 2020).

FAO, 2020. Hunger and food insecurity. URL https://www.fao.org/hunger/en/ (Accessed 5 July 2020).

Fernández-Ríos, A., Laso, J., Campos, C., Ruiz-Salmón, I., Hoehn, D., Cristóbal, J., Batlle-Bayer, L., Bala, A., Fullana-i-Palmer, P., Puig, R., Aldaco, R., Margallo, M., 2021. Towards a Water-Energy-Food (WEF) nexus index: a review of nutrient profile models as a fundamental pillar of food and nutrition security. Sci. Total Environ. 789, 147936 https://doi.org/10.1016/J.SCITOTENV.2021.147936.

Golfam, P., Ashofteh, P.S., Loáiciga, H.A., 2021. Modeling adaptation policies to increase the synergies of the water-climate-agriculture nexus under climate change. Environ. Dev. 37, 100612 https://doi.org/10.1016/J.ENVDEV.2021.100612.

González-Bravo, R., Sauceda-Valenzuela, M., Mahlknecht, J., Rubio-Castro, E., Ponce-Ortega, J.M., 2018. Optimization of water grid at macroscopic level analyzing water–energy–food nexus. ACS Sustain. Chem. Eng. 6, 12140–12152. https://doi.org/10.1021/ACSSUSCHEMENG.8B02484.

Health Secretary, 2010. Food guide for the Mexican population. URL. http://fisiologia.facmed.unam.mx/wp-content/uploads/2019/02/2-Valoraci%C3%B3n-nutricional-Anexos.pdf (accessed 8.14.21).

Hoff, H., 2011. Background paper for the Bonn 2011 Nexus Conference: The Water, Energy and Food Security Nexus. URL https://www.water-energy-food.org/uploads/media/understanding_the_nexus.pdf (accessed 3.4.20).

Hooker, J.N., 2010. Optimality conditions for distributive justice. Int. Trans. Oper. Res. 17 (4), 485–505. https://doi.org/10.1111/j.1475-3995-2009.00742.x.

Kaddoura, S., El Khatib, S., 2017. Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making. Environ. Sci. Policy 77, 114–121. https://doi.org/10.1016/J.ENVSCI.2017.07.007.

Kurian, M., 2017. The water-energy-food nexus: trade-offs, thresholds and transdisciplinary approaches to sustainable development. Environ. Sci. Policy 68, 97–106. https://doi.org/10.1016/J.ENVSCI.2016.11.006.

Li, P.C., Ma, H.W., 2020. Evaluating the environmental impacts of the water-energy-food nexus with a life-cycle approach. Resour. Conserv. Recycl. 157, 104789 https://doi.org/10.1016/J.RESCONREC.2020.104789.

Ma, Y., Li, Y.P., Zhang, Y.F., Huang, G.H., 2021. Mathematical modeling for planning water-food-ecology-energy nexus system under uncertainty: a case study of the Aral Sea Basin. J. Clean. Prod. 308, 127368 https://doi.org/10.1016/J.JCLEPRO.2021.127368.

Mohammadpour, P., Mahjabin, T., Fernandez, J., Grady, C., 2019. From national indices to regional action—an Analysis of food, energy, water security in Ecuador, Bolivia, and Peru. Environ. Sci. Policy 101, 291–301. https://doi.org/10.1016/J.ENVSCI.2019.08.014.

Mroue, A.M., Mohtar, R.H., Pistikopoulos, E.N., Holtzapple, M.T., 2019. Energy portfolio assessment tool (EPAT): Sustainable energy planning using the WEF nexus approach – Texas case. Sci. Total Environ. 648, 1649–1664. https://doi.org/10.1016/J.SCITOTENV.2018.08.135.

Munguía-López, A., del, C., Sampat, A.M., Rubio-Castro, E., Ponce-Ortega, J.M., Zavala, V.M., 2019. Fairness-guided design of water distribution networks for agricultural lands. Comput. Chem. Eng. 130, 106547 https://doi.org/10.1016/J.COMPCHEMENG.2019.106547.

Munguía-López, A., del, C., Núñez-López, J.M., Ponce-Ortega, J.M., 2020. Identifying fair solutions in the optimal design of integrated residential complexes. Chem. Eng. Process. - Process. Intensif. 157, 108116 https://doi.org/10.1016/J.CEP.2020.108116.

Munguía-López, A., del, C., Sánchez-Bautista, A., de, F., El-Halwagi, M.M., Ponce-Ortega, J.M., 2021. Strategic planning of an integrated fuel production system with a fair-sustainable approach. ACS Sustain. Chem. Eng. 9, 5116–5127. https://doi.org/10.1021/ACSSUSCHEMENG.1C00137.

Nash Jr., J.F., 1950. The bargaining problem. Econometrica 18 (2), 155–162. DOI: 0012-9682(195004)18:2<155:TBP>2.0.CO;2-H.

Ogbolumani, O.A., Nwulu, N.I., 2021. Multi-objective optimisation of constrained food-energy-water-nexus systems for sustainable resource allocation. Sustain. Energy Technol. Assess. 44, 100967 https://doi.org/10.1016/J.SETA.2020.100967.

Pahl-Wostl, C., 2019. Governance of the water-energy-food security nexus: a multi-level coordination challenge. Environ. Sci. Policy 92, 356–367. https://doi.org/10.1016/j.envsci.2017.07.017.

Radini, S., Marinelli, E., Akyol, Ç., Eusebi, A.L., Vasilaki, V., Mancini, A., Frontoni, E., Bischetti, G.B., Gandolfi, C., Katsou, E., Fatone, F., 2021. Urban water-energy-food-climate nexus in integrated wastewater and reuse systems: cyber-physical framework and innovations. Appl. Energy 298, 117268. https://doi.org/10.1016/J.APENERGY.2021.117268.

Rawls, J., 1971. A theory of justice. Harvard Univ. Press, Cambridge.

Romero-Lankao, P., Bruns, A., Wiegleb, V., 2018. From risk to WEF security in the city: the influence of interdependent infrastructural systems. Environ. Sci. Policy 90, 213–222. https://doi.org/10.1016/J.ENVSCI.2018.01.004.

Sampat, A.M., Zavala, V.M., 2019. Fairness measures for decision-making and conflict resolution. Optim. Eng. 204 (20), 1249–1272. https://doi.org/10.1007/S11081-019-09452-3.

Smith, G., Bayldon Block, L., Ajami, N., Pombo, A., Velasco-Aulcy, L., 2020. Trade-offs across the water-energy-food nexus: a triple bottom line sustainability assessment of desalination for agriculture in the San quintín Valley, Mexico. Environ. Sci. Policy 114, 445–452. https://doi.org/10.1016/J.ENVSCI.2020.08.008.

Stark, O., Jakubek, M., Falniowski, F., 2014. Reconciling the Rawlsian and the utilitarian approaches to the maximization of social welfare. Econ. Let. 122 (3), 439–444. https://doi.org/10.1016/j.econlet.2013.11.019.

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. Sci. Total Environ. 775, 145827 https://doi.org/10.1016/J.SCITOTENV.2021.145827.

WHO, 2021. Healthy diet. URL https://www.who.int/initiatives/behealthy/healthy-diet (Accessed 5. December 2020).

Yu, L., Xiao, Y., Zeng, X.T., Li, Y.P., Fan, Y.R., 2020. Planning water-energy-food nexus system management under multi-level and uncertainty. J. Clean. Prod. 251. https://doi.org/10.1016/J.JCLEPRO.2019.119658.

Yue, Q., Zhang, F., Wang, Y., Zhang, X., Guo, P., 2021. Fuzzy multi-objective modelling for managing water-food-energy-climate change-land nexus towards sustainability. J. Hydrol. 596, 125704 https://doi.org/10.1016/J.JHYDROL.2020.125704.

Zakeri, M.A., Mirnia, S.K., Moradi, H., 2022. Assessment of water security in the large watersheds of Iran. Environ. Sci. Policy 127, 31–37.

Zhang, J., Campana, P.E., Yao, T., Zhang, Y., Lundblad, A., Melton, F., Yan, J., 2018. The water-food-energy nexus optimization approach to combat agricultural drought: a case study in the United States. Appl. Energy 227, 449–464. https://doi.org/10.1016/J.APENERGY.2017.07.036.

Zhou, Y., Chang, L.C., Uen, T.S., Guo, S., Xu, C.Y., Chang, F.J., 2019. Prospect for small-hydropower installation settled upon optimal water allocation: an action to stimulate synergies of water-food-energy nexus. Appl. Energy 238, 668–682. https://doi.org/10.1016/J.APENERGY.2019.01.069.

Zucchinelli, M., Spinelli, R., Corrado, S., Lamastra, L., 2021. Evaluation of the influence on water consumption and water scarcity of different healthy diet scenarios. J. Environ. Manag. 291, 112687.