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Unraveling the Water-Energy-Food-Environment Nexus for Climate Change Adaptation in Iran: Urmia Lake Basin Case-Study

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Abstract: A holistic approach to the management of water, energy, food, and the environment is required to both meet the socioeconomic demands of the future as well as sustainable development of these limited resources. The Urmia Lake Basin has faced environmental, social, and economic challenges in recent years, and this situation is likely to worsen under the impacts of climate change. For this study, an adaptability analysis of this region is proposed for the 2040 horizon year. Two models, the water evaluation and planning (WEAP (Stockholm Environmental Institute, Stockholm, Sweden)) and the low emissions analysis platform (LEAP (Stockholm Environmental Institute, Boston, MA, USA)), are integrated to simulate changes in water, energy, food, and the environment over these 20 years. Two climate scenarios and nine policy scenarios are combined to assess sustainable development using a multi-criteria decision analysis (MCDA) approach. Results show that, through pursuing challenging goals in agricultural, potable water, energy, and industrial sectors, sustainable development will be achieved. In this scenario, the Lake Urmia water level will reach its ecological water level in 2040. However, social, technical, and political challenges are considered obstacles to implementing the goals of this scenario. In addition, industry growth and industry structure adjustment have the most impact on sustainable development achievement.

Keywords: water-energy-food-environment nexus; sustainable development; Lake Urmia; multi-criteria decision analysis; climate modeling

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1. Introduction

Population growth and economic development in recent years have led to an increase in demand for natural resources. As a consequence, providing water, energy, and food, as well as protecting the environment, have become a challenge for governments. In this context, the concept of sustainable development has been endorsed as a policy objective to protect future generations [1,2], and the interaction between water, energy, food, and environment (WEFE) sectors have been identified as the nexus approach in the development of the integrated strategies [3,4].

To date, various approaches to study this nexus have been developed by researchers [5,6]. The most important aims of these studies are to (1) highlight the complex interaction of the different sectors, (2) develop and analyze multidisciplinary scenarios [7], (3) identify scenarios that (a) attain sustainable development in a region [8], (b) maximize the synergy of the sectors [9], (c) optimize resource sustainability [10], and (d) while minimizing the environmental impacts [11].

One of the emerging tools in the nexus approach is the use of two models: (1) the water evaluation and planning (WEAP) and (2) the low emissions analysis platform (LEAP).

These two models were developed by the Stockholm Environment Institute (SEI) [12]. These two tools have been successfully used to study socio-political issues involving the nexus between multiple resource and environmental factors. Such studies have involved different energy sources, land-use changes, and climate change scenarios [13–16]. In addition, these tools have been used for lakes in large watersheds [17–19].

Our study focuses on Lake Urmia, located in northwest Iran. Lake Urmia, an endorheic lake, was once the world's second-largest salt lake, was designated a United Nations Educational, Scientific and Cultural Organization (UNESCO) ecosystem, and it and its surrounding wetland contained considerable cultural, economic, aesthetic, and ecological values [20,21]. In 1970, it had an area of 5000 km^2; by 2018, its area was only 1000 km^2. Between 1996 and 2016, the water level dropped 8 m as the result of a prolonged climate change-related drought and increased water consumption, especially by the agricultural sector [22–27].

Alizade et al. [28] determined that anthropogenic impacts were responsible for 80% of the change and climate factors by 20%. In contrast, Arkian et al. [29] concluded that meteorological variables were a stronger determinant. Clearly, climate and climate- agricultural water use interact.

The losses associated with the drying of Lake Urmia and its surrounding wetlands have been recognized, and efforts to restore the watershed have been initiated [22]. Studies to understand the tradeoffs between different crops, their food production, and their water use have been conducted [19,30–32]. Their scope and the presence of multiple interacting factors have restricted their usefulness.

Mapping out multiple alternatives when considering several factors, evaluating the outcomes, and then selecting the right strategy is a difficult process [33]. Multi-criteria decision analysis (MCDA) provides a framework for accomplishing this. This framework has been applied in sustainable energy planning [34], in a nexus approach involving food production, energy use, and land use [35], and in determining sustainable water use in a watershed [36]. Regarding the development process, the form and scope of application MCDA approaches are divided into four categories: (1) the value system approach, (2) the outranking relations approach, (3) the disaggregation–aggregation approach, and (4) the multi-objective optimization approach [37]. The structure of a decision problem (e.g., the knowledge that the decision-maker seeks to attain from the analysis and how this knowledge can be translated into a preference structure) determines the most suitable MCDA approach [38]. The analytic hierarchy process (AHP) and the technique for order of preference by similarity to ideal solution (TOPSIS) are known as the value system and outranking relations approaches, respectively. The combination of these two methods has become a widely accepted integrated MCDA method [39]. Specifically, in recent years this method is employed in the sustainable evaluation of the systems [40,41].

None of the previous studies have developed a multisectoral approach to design a holistic policymaking framework for sustainable development in this district. Covering this research gap is the purpose of this paper, as it explores all direct and indirect impacts or potential conflicts between sectors, and environmental and socioeconomic implications of implementing restoration policies. In addition, integrating a variety of modeling tools, data sources, and scenarios has created a detailed analysis of climate change adaptation strategies possible. The former studies had focused on a single sector, neglecting the complex interactions between sectors and their potential to save the Urmia Lake. Moreover, the few recent studies that implemented holistic systems modeling neglected aspects of sustainable development [19]. To address this problem, a decision-making approach should be developed to assess the most effective policies in terms of social, economic, environmental, and technical criteria.

In this study, we explore future climate scenarios on water, energy, food, and the environment in the Urmia Lake Basin using the WEFE nexus approach. For each climate scenario, the integrated LEAP and WEAP models were used to simulate the effects on the four sectors. The MCDA was applied to assess the results of the investigated scenarios for developing a sustainable future in this region. In this regard, AHP is used to define the weights of each criterion, and TOPSIS is used to evaluate each scenario. The primary targets of this study can be summarized as:

- To propose a new framework for investigating the role of different sectors in the future of Urmia Lake Basin;
- To quantify the cross-sector interlinkages and resource dependence of water, energy, and agriculture sectors and the related environmental impacts;
- To assess the impact of climate change and policy scenarios on the future of Urmia Lake Basin and evaluate the consequences of implementing each policy scenario on achieving sustainable development.

2. Materials and Methods

The overall methodology of this study is represented in Figure 1, and it can be divided into three phases: data collection and nexus modeling, scenario design, and application of MCDA using an integrated AHP-TOPSIS approach. The data collection and nexus modeling phase describe the complicated relationships between water, energy, food, environment, and climate change sectors. The data used for this phase were collected from various governmental organizations. The prepared model in this phase is used in the next phase to develop a scenario-based analysis. In this step, two climate scenarios and nine policy scenarios form a matrix with eighteen components representing possible future conditions. The policy scenarios are based on considering moderate and challenging goals for sustainable development strategies in agriculture, potable water, energy, and industry sectors. In order to assess the future performance of the policy scenarios, the MCDA analysis is used to rank the alternatives.

2.1. Study Area

Urmia Lake Basin, with a population of more than six million people [42], is located in the northwest of Iran between 44°20′ and 47°90′ E longitude and 35°62′ and 38°50′ N latitude (Figure 2) with an area of 51,762 km^2. This basin is one of the six main river basins in Iran. The basin can be divided into twelve sub-basins [19]. Based on the political boundary, the basin area is shared among three provinces, including West Azarbaijan (53%), East Azarbaijan (37%), and Kurdistan (10%) [43], and the main sources of income are agriculture and industry [44].

The Urmia Lake Basin is at an elevation of about 1300 m and is surrounded by mountains, including those of the Ararat Mountains in the far north and the Zagros Mountains in the west, southwest, and south, that rise to maximum elevations between 3200 and 3600 m. The climate of the Urmia Lake Basin is continental and harsh [45] and is characterized by cold winters and dry, temperate summers [46]. The long-term mean annual temperature of Urmia Lake Basin varies from 6.5 °C in upper elevations to 13.5 °C at lower elevations. Lake Urmia plays a critical role in moderating the temperature extremes [47]. According to long-term precipitation data, the annual mean precipitation in Urmia Lake Basin is 352 mm [48]. It varies from 200 mm in the area surrounding the Lake Urmia to 850 mm in the northwestern of Urmia Lake Basin [25]. The summer season, with rare precipitation, is from May to October, and the humid season lasts from November to April/May [44].

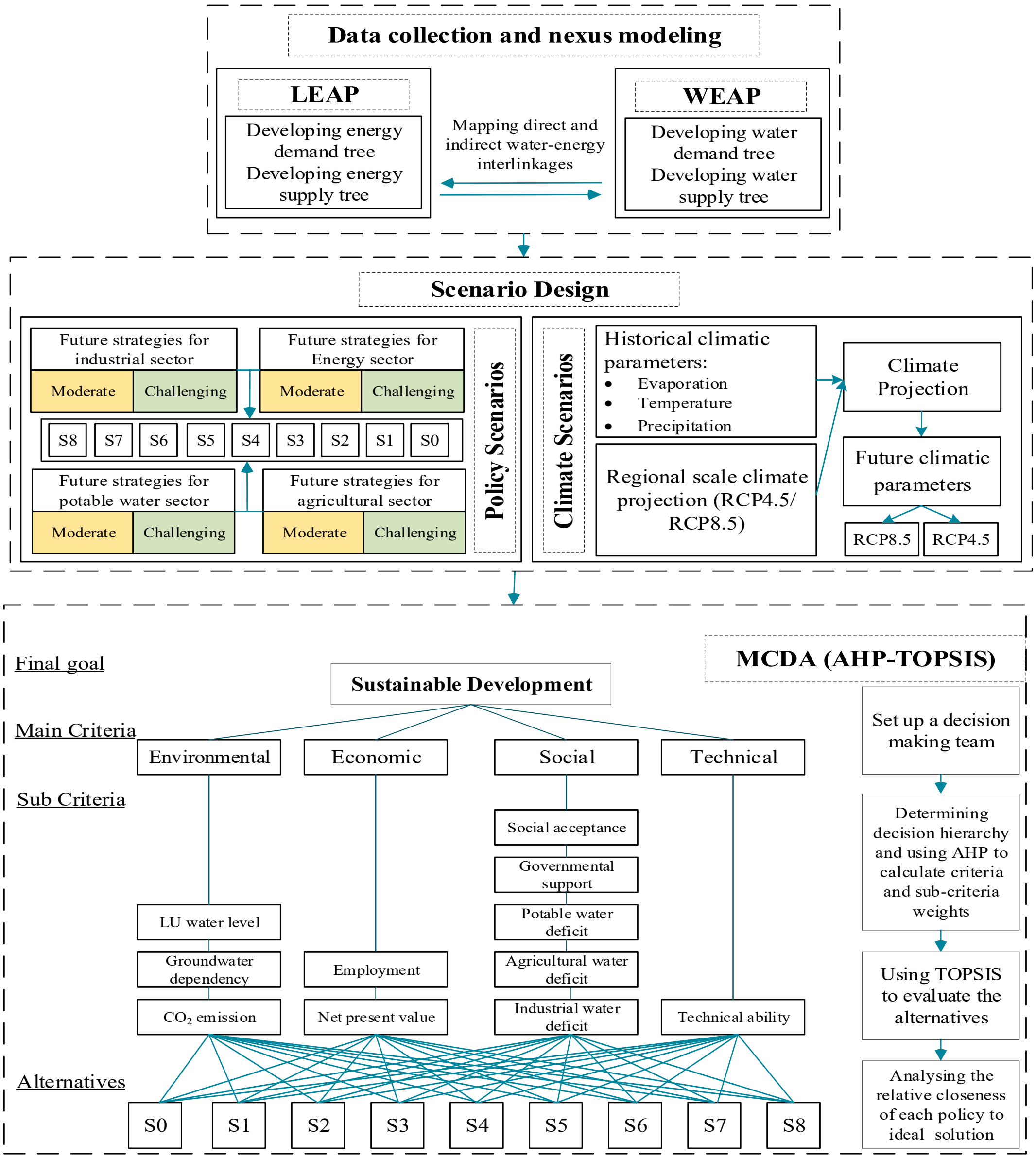

Figure 1. The overall methodology of the study.

Lake Urmia is an internationally registered protected area as a UNESCO biosphere reserve and a national park with a length of 140 km and width of 55 km [45], maximum and the average depth of 16 and 5 m, respectively [49], and is the habitat of different species of animals and plants. At its greatest extent, Lake Urmia was the largest lake in the Middle East. Today, it is 20% of its original size, and this significant decrease in the amount of water the lake receives has increased the salinity of the lake's water, reducing the population of Artemia and its viability as home to thousands of migratory birds.

The freshwater input to this lake comes from surface resources (17 permanent rivers and 12 seasonal rivers [50]), of which the Zarine, Simine, and Ajichai rivers provide the largest proportion. The water level in this lake started to decrease sharply from 1995 [50] and has registered negative trends since then [51].

The agricultural sector, which is the largest consumer of surface water resources and groundwater resources (there are over 128,000 wells in the basin [19]), is known as the main cause for the significant reduction in discharge to the lake.

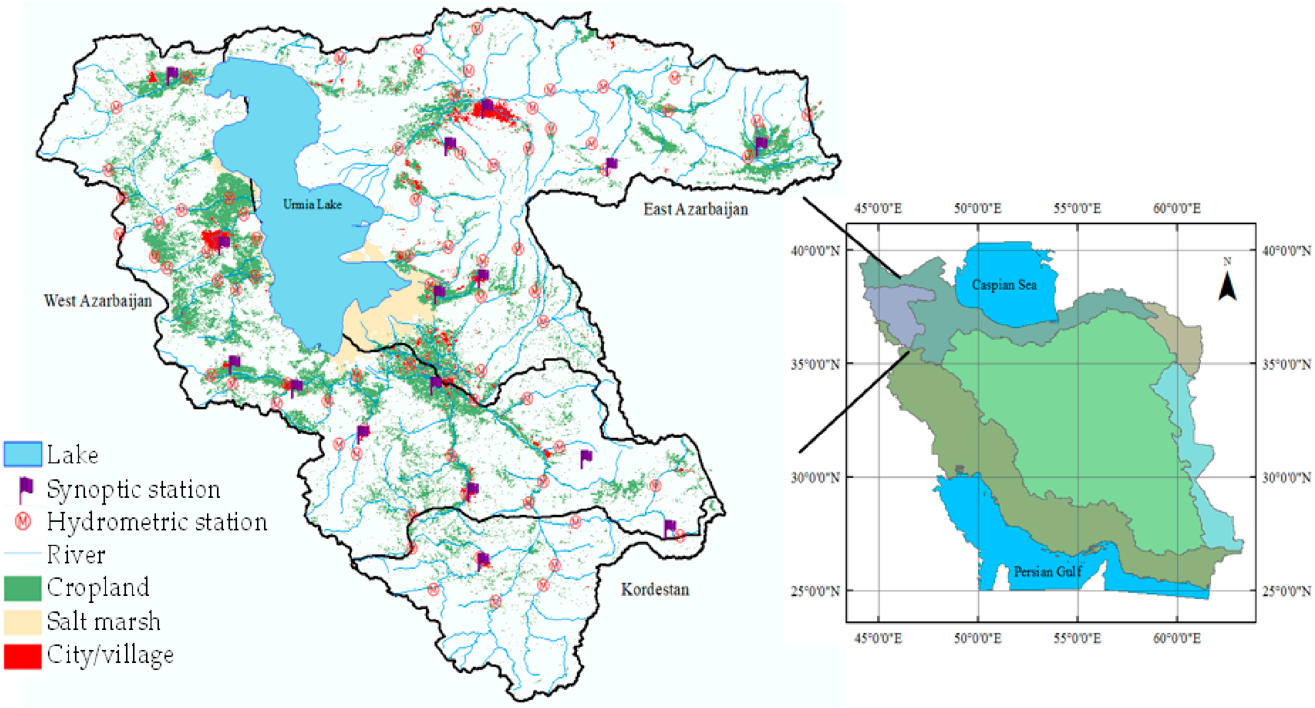

Figure 2. The map of Urmia Lake Basin and the location of synoptic and hydrometric stations.

2.2. Data

The data were classified into five groups: society and economy, energy, agriculture, meteorology, and water. The main sources of data are the Ministry of Energy, Water and Wastewater Company, Statistical Center of Iran, Iran Central Bank, Urmia lake restoration program (ULRP), Meteorological Organization, and the Ministry of Agriculture. The study area covers parts of three provinces, namely, West Azarbaijan, East Azarbaijan, and Kordestan. Therefore, each sector's related data are collected at the provincial level. Because provinces include land outside of the part of the basin, the data were modified and were restricted to the study area. Table 1 represents more details about raw data. The accuracy of the raw data is checked to provide reliable estimates.

2.3. Nexus Method

Energy, water, food, and environment are fundamentally interrelated in this study area. Energy is required for water treatment and distribution, producing food, and developing modernized agriculture as a key strategy to save the lake. Under the water-stressed condition, water is consumed for cultivating food crops, industrial and residential purposes, producing energy. In addition, the Lake Urmia restoration is highly dependent on implementing water management solutions. Food is required to physically and economically support the growing population of the Urmia Lake Basin. Considering the environmental aspects of the current situation and future plans is essential for achieving sustainable development goals (SDGs). Taking the nexus approach, a multidisciplinary analysis helps to build synergies between different sectors.

Figure 3 represents the WEFE nexus approach, which is developed in this study. The mutual relationship between two sectors, two subsectors, sector-subsector, and also socioeconomic changes and climate changes impact on sectors and subsectors, is illustrated. Socioeconomic factors at the first level mainly affect the water energy and food demand, while climate change directly impacts both supply and demand for water and energy.

Table 1. Raw data and sources.

Category	Primary Data	Sources
Economy and society	Population and household size	[52]
	Gross domestic product (GDP) structure	[53]
	Inflation and discount ration	[54]
Energy	Domestic urban and rural energy consumption of appliances based on fuel type, commercial energy consumption based on fuel type, energy consumption for thirteen main industries based on fuel type, electricity consumption of public lighting, pressurized and unpressurized energy consumption for thirteen main crops based on fuel type, energy consumption in greenhouse based on fuel type, electricity consumption for water treatment and distribution, percentage of loss for electricity transmission and distribution, information about power generation (e.g., fuel type, efficiency, availability)	[55,56]
Water	Domestic urban and rural water consumption, physical water loss	[57,58]
	Information about rivers, aquifers, and dams	[59]
	The efficiency of different irrigation systems, pressurized and unpressurized water consumption for thirteen main crops, greenhouse water consumption, water consumption for thirteen main industries	[60]
	Water consumption and withdrawal in energy generation	[55,57,58]
Agriculture	The area under cultivation for different crops and different irrigation systems, greenhouse area under cultivation	[60]
Lake Urmia	Volume, area, and level of water of Lake Urmia	[61]
Meteorology	Daily precipitation, maximum and minimum daily temperature, location of meteorological stations	[62]

In this study, the integrated LEAP and WEAP models are used to explore the outcomes of WEFE scenarios, which are not apparent when these systems are studied independently. Accordingly, to study the energy and water sectors LEAP and WEAP are used, respectively. For agriculture, environment, climate, and socioeconomic modeling, both softwares are used simultaneously using the integrated module developed by SEI, regarding the same base and end years and the same set of time steps [63].

2.3.1. WEAP

In this study, WEAP software was used to develop an integrated model for estimating the water demand of various sectors and the available water from existing resources. WEAP provides a widely used tool for regional hydrological modeling, comprehensive water resource planning, and scenario analysis to engage policymakers in an open planning process [64,65].

This software was used to evaluate the wide range of demand and supply options in the Urmia Lake Basin area and the complicated interactions of these two factors with the Lake Urmia level fluctuations to balance environment and development objectives.

By calculating the water mass balance for each node and linking through the specified time step, optimizing coverage of demand and flow requirements will be available. For this aim, WEAP uses a linear programming algorithm that is subject to some constraints, such as user-defined demand priorities and supply preferences. These two constraints allow the users to establish the order of demands that will be met and to investigate the impact of water shortage of a resource on other local water resources [66,67].

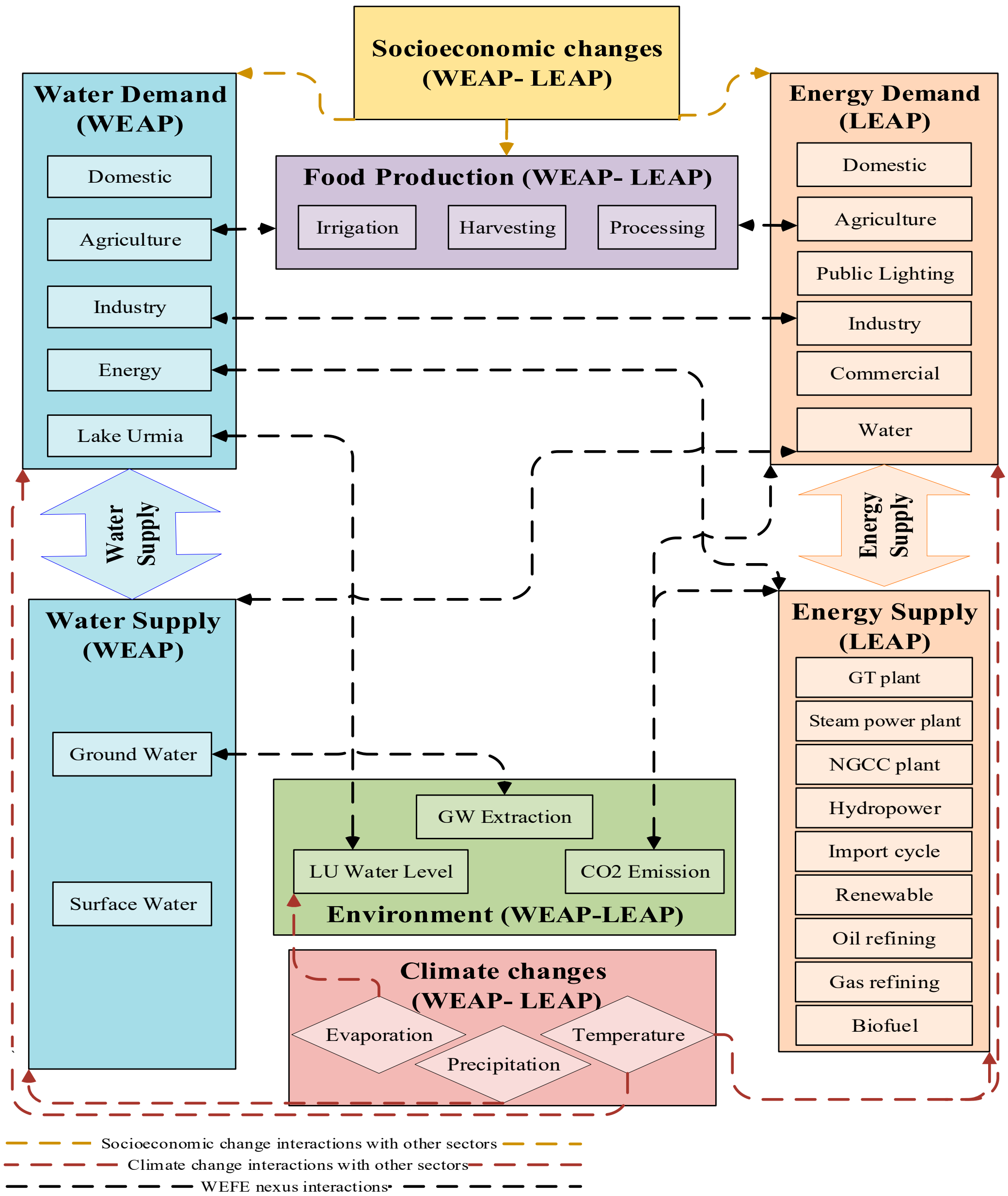

Figure 3. WEFE nexus framework and model structure.

The initial data for both resources and demands are fed into the model in monthly variation for the current account. The settings of supply and demand points in the WEAP model are presented by its geographical extent in Figure 4. This model consists of 37 demand sites classified into four general groups: domestic, agriculture, industrial, and energy. In addition, each river's flow requirement point represents the lake's ecological and environmental water demand. The priority for allocating the available water to the lake and other demand sites is defined based on the local policies for each sub-basin. The domestic water demand is estimated for each rural and urban site based on population, water consumption per capita, and real water loss. The agricultural demand for each agricultural node is calculated for different crops and irrigation methods according to the cultivated area, water use rate, and water loss. The considered crops in this study are wheat, barley, sugar beet, beans, watermelon, cucumber, tomato, alfalfa, potato, sunflower, apple, cherry, almond, walnut, and grape and considered irrigation methods are flooding, sprinkler, drip, and greenhouse cultivation. This classification is followed in this study to assess the impacts of crop pattern adjustment and irrigation efficiency improvement strategies. The industrial water demand for each site is defined according to the existing industrial zones in the area based on each unit's water use rate. The considered industries are food, drink, textile, wear, leather, paper, chemical, nonmetallic, metals, machinery and equipment, mine, wood, and livestock. The water demand for the energy sector is also defined based on each energy plant in the area.

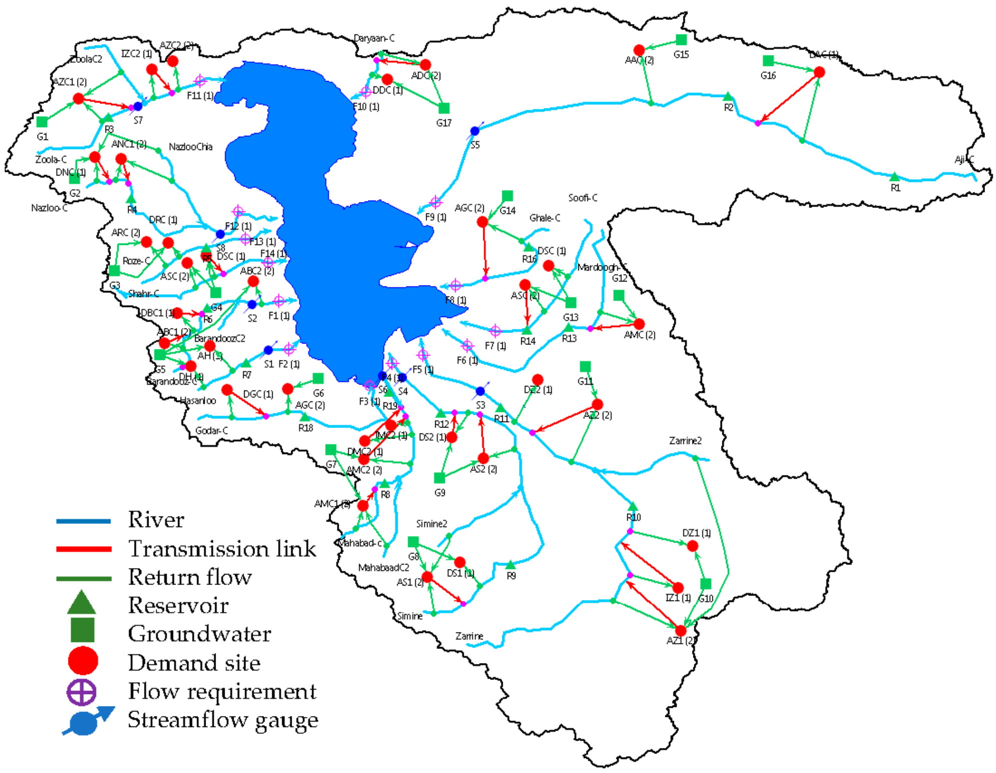

Figure 4. WEAP model for the Urmia Lake Basin.

The water resources of Urmia Lake Basin are 21 rivers and 17 aquifer points. The demand nodes are linked to the resource nodes through transmission and return flow links. The model was calibrated from 2011–2016 and validated from 2017–2019 by maximizing the fit between the observed data of hydrometric stations and the simulated flow of streamflow gauges located in the model.

Changes in temperature and precipitation as direct impacts of climate change significantly affected both water demand and supply. The impact rate varies from one region to another regarding the geographic location and climatic condition [68].

Considering the demand sector, agriculture as the main water consumer in the Urmia Lake Basin is affected more heavily. Higher temperature causes larger amounts of surface water, which returns to the atmosphere through evapotranspiration. WEAP calculates evapotranspiration using the Penman–Monteith equation [69].

The water demand for irrigation (IRR, mm) was calculated considering both temperature and rainfall change using Equation (1) [70]:

$$\text{IRR} = \text{ET} - (\text{P} - \text{D}_\text{P} - \text{RO}) - \text{GW} - \Delta\text{SW} \quad (1)$$

where P is precipitation (mm), D_p is deep percolation from the crop root zone (mm), RO is surface runoff (mm), GW is the groundwater recharge during the growth of the crop, and ΔSW is the soil moisture storage capacity (mm).

The impact of climate change on domestic and industrial water demand was estimated from the literature using the elasticity concept [71,72]. Equation (2) and Equation (3) represent the temperature elasticity and precipitation elasticity of water demand, respectively [68].

$$e_T = -\frac{\Delta Q}{\Delta T} \quad (2)$$

$$e_P = -\frac{\Delta Q}{\Delta P} \quad (3)$$

where e_T is temperature elasticity, ΔQ is the percentage change in water demand (mm), ΔT is the percentage change in temperature (°C), e_P is precipitation elasticity ($m^3\ mm^{-1}$), and ΔP is the percentage change in precipitation (mm).

2.3.2. LEAP

LEAP is the production of SEI for comprehensive energy and Greenhouse gas (GHG) mitigation planning to describe the impact of socioeconomic factors on energy consumption and measuring the energy balance under different future scenarios. This software provides a framework for evaluating energy policies and sustainable energy plans [73,74] and is used in more than 190 countries [75].

The energy modeling in this software is performed by determining energy supply options, power dispatch rules, and energy demand. Electricity generation is a transformation sector in which fuels such as natural gas and hydro are converted into electricity. Electricity generation alternatives are gas turbine plants, steam power plants, natural gas combined-cycle plants, hydropower, and renewables (solar, wind, etc.). All power plants in the region and future power expansions to meet balancing requirements were modeled. This software uses an optimization approach to suggest which plants to build and when to meet demands whenever capacity is needed [76]. Most of the electricity demand in Urmia Lake Basin is met by thermal power plants. However, electricity is imported into the region if the demand is higher than the available supply at the end of each period.

Energy demands are modeled for the residential (based on rural and urban), agricultural, industrial, commercial, public lighting, and water sectors. The energy demand for the sectors is estimated by considering factors including population, ambient temperature, water deliveries, groundwater depth, energy demand of each crop, and energy demand of each industrial unit. These input parameters and also efficiency and capacity factors for each power plant are gathered from 2011 to 2019 and used in the model based on the Ministry of Energy reports.

The technology and environmental database (TED) module of LEAP is used to estimate the emissions of the consumed fuels and the environmental data for various pollutants. This module contains a database of various sources on emission factors. The LEAP's database also includes global warming effects [16].

2.4. Scenario Design

By developing scenarios for possible futures based on physical, social, and climate changes, a policy-oriented framework for analyzing the various strategies leading to sustainability is presented in this study for the 2040 horizon year. This framework is provided by combining two future climate scenarios with nine policy scenarios, which form a matrix containing eighteen components. Based on the assumptions related to each component of the scenario matrix, the integrated model is executed, and the results are used in MCDA.

2.4.1. Climate Change Scenarios

To develop an integrated approach based on external factors that have the potential to constrain or enable the possible future states and outcomes, considering climate change is crucial for having a realistic approach to future challenges. For studying the climate change in Urmia Lake Basin, the climate projections are calculated based on representative concentration pathways (RCPs) defined in the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) [77]. By considering a set of global climate scenarios regarding emissions of GHGs, RCPs provide information on possible development trajectories for the forcing agents of climate change [78]. The four developed RCPs are labeled after a possible range of radiative forcing values in the year 2100. The considered scenarios in this study are RCP 4.5 and RCP 8.5, respectively representing 4.5 W/m^2 [79] and 8.5 W/m^2 [80] radiative forcing in 2100. The selected climate change scenarios are representative of an intermediate and a pessimistic evolution of greenhouse emission levels. Climate change scenarios also provide the background for implementing socioeconomic assumptions based on possible outputs for each RCP.

In this study, the baseline period is 1991–2010, and the historical data used for projection are maximum daily temperature, minimum daily temperature, daily precipitation, and daily evaporation of 5 synoptic stations. The coordinated regional downscaling experiment (CORDEX) is used for generating regional-scale climate projections for the MNA-44 domain by using the ICHEC-EC-Earth driving model at a daily time step.

2.4.2. Policy Scenarios

Different policies are designed by different governmental agencies, such as the Ministry of Energy, Ministry of Agriculture, Department of Environment Protection, ULRP, and the local governors of three provinces adjacent to Lake Urmia. Simulating these policies enables decision-makers to assess each strategy's direct and indirect impacts on short-term and long-term sustainable development.

Most recommendations are agricultural-oriented ones centered around increasing the efficiency of water use in crop production. However, increasing the synergy of different sectors working together is essential for reaching a sustainable solution compatible with the region's ecology. According to Table 2, ten strategies were developed in the agricultural, potable water, industry, and energy sectors. Two different goals were used to establish the degree of importance for each strategy using the MCDA approach. These two goals led to different futures, depending on the result of implementing each strategy. In the challenging goals, the government and people invest more heavily to guarantee a sustainable future for the Urmia Lake Basin. A moderate goal is a middle approach between business as usual (BAU) and challenging goals. The historical data were used to estimate the extent of changes in water consumption or withdrawal and energy consumption after implementing each policy.

In order to design an integrated basis for reaching the best decisions, the combination of strategies in each sector with other sectors is developed in this study and represented in Table 3. According to this table, S0 represents the BAU scenario. In this scenario, all the sectors continue to develop slowly. The agricultural productivity remains low, potable water loss and demand for rural and urban areas remain high. The industry growth and structure adjustment remain underestimated, and renewable energy development remains insignificant. S1 and S8 are scenarios in which moderate and challenging goals are followed in all sectors, respectively. The six other scenarios are designed to explore the degree of importance related to each sector and reaching the best combination of strategies for achieving SDGs.

2.5. MCDA

To assess each scenario's potential to embrace sustainable practices in Urmia Lake Basin, the MCDA approach is implemented and is known as a major component of decision support systems. This method aims to rank alternatives based on the selected evaluation criteria, and their importance is judged by the experts. Different MCDA methods are developed for ranking the alternatives, and in the present study, an integrated AHP-TOPSIS is used for this aim.

Table 2. Strategies and related goals for sustainable development in Urmia Lake Basin.

Classification	Strategy Name	Moderate Goal	Challenging Goal
Agriculture	Cultivation area reduction	Decrease in cultivation area by 0.5% each year	Decrease in cultivation area by 1% each year
	Crop pattern adjustment	Replacing the cultivation of high-water consumption crops with low-water consumption crops to reach the limitation of providing local requirement by 2040	Banning the cultivation of high-water consumption crops and replace them with low-water consumption crops by 2040
	Greenhouse cultivation development	Increasing the share of greenhouse cultivation by 2% each year	Increasing the share of greenhouse cultivation by 3% each year
	Irrigation efficiency improvement	Improving systems of irrigation to sprinkler and drip irrigation by 20% at the end of the time horizon	Improving systems of irrigation to sprinkler and drip irrigation by 40% at the end of the time horizon
Potable water	Water loss reduction in the water distribution network	Reducing leaks and bursting to reduce real water loss by 0.5% each year	Reducing leaks and bursting to reduce real water loss by 1.2% each year
	Water demand management	Improving water conservation technologies and decreasing water use intensity by 10% at the end of the time horizon, compared to BAU	Improving water conservation technologies and decreasing water use intensity by 20% at the end of the time horizon, compared to BAU
Industry	Industry growth/industry structure adjustment to save water and energy	The industry grows by 23% over the BAU level by 2040, and the share of water-intensive industries is decreased to 16%	The industry grows by 53% over the BAU level by 2040, and the share of water-intensive industries is decreased to 8%
Energy	Energy-saving improvement on the demand side	Energy efficiencies are improved by 10% over BAU levels by 2040 in different sectors	Energy efficiencies are improved by 20% over BAU levels by 2040 in different sectors
	Power generation improvement	Renewable energies capacity increases by 50% over BAU levels by 2040, replacing 50% of the capacity of gas turbine plants with natural gas combined-cycle plants	Renewable energies capacity increases by 70% over BAU levels by 2040, replacing 100% of the capacity of gas turbine plants with natural gas combined-cycle plants

Table 3. The combination of strategies for each scenario.

Scenario \ Sector	Potable Water	Agriculture	Industry	Energy
S0	BAU			
S1	(yellow)	(yellow)	(yellow)	(yellow)
S2	(green)	(green)	(yellow)	(yellow)
S3	(green)	(yellow)	(green)	(yellow)
S4	(green)	(yellow)	(yellow)	(green)
S5	(yellow)	(green)	(green)	(yellow)
S6	(yellow)	(green)	(yellow)	(green)
S7	(yellow)	(yellow)	(green)	(green)
S8	(green)	(green)	(green)	(green)

The cells in yellow and green colors represent moderate goal and challenging goal, respectively.

2.5.1. Evaluation Criteria

To assess the potential of each scenario to fulfill the sustainability objectives, four prime criteria are identified. For each criterion, specific indicators are developed, derived from technical and financial experts, local governments, and literature surveys. The nine alternatives assessment is performed by the eleven indicators that contribute to the main objective, as presented in Table 4. The diversity of indicators is crucial to develop a coherent study, enhancing synergies, protecting the ecosystem, cutting the costs, reducing the negative effects of policies on different nexus domains, and achieving WEFE nexus sustainability.

Table 4. The criteria and sub-criteria list.

Main Criteria	Indicator	Code	Unit	Criteria Factor
Environmental	Difference between Lake Urmia water level and its ecological water level	$C_{1.1}$	Million cubic meter (MCM)	Negative
	Dependency on groundwater resources	$C_{1.2}$	MCM	Negative
	CO_2 emission	$C_{1.3}$	Tones CO_2	Negative
Economic	Employment	$C_{2.1}$	-	Positive
	Net present value	$C_{2.2}$	Million United States dollar (USD)	Positive
Social	Social acceptance	$C_{3.1}$	-	Positive
	Governmental support	$C_{3.2}$	-	Positive
	Potable water deficit	$C_{3.3}$	MCM	Negative
	Agricultural water deficit	$C_{3.4}$	MCM	Negative
	Industrial water deficit	$C_{3.5}$	MCM	Negative
Technical	Technical ability	$C_{4.1}$	-	Positive

Assessing the impact of alternatives on the environment is crucial for developing a sustainable approach for the Urmia Lake Basin. For many years, inefficient agricultural growth has threatened the environment in which the main negative effect has been on the Lake Urmia water level and underground water level. In this study, three indicators are considered to address environmental concerns, and they are calculated monthly for the years 2020–2040.

The $C_{1,1}$, which relates to the water level in Lake Urmia, is estimated according to Equation (4):

$$C_{1,1} = \sum_{y1}^{y21}\sum_{m1}^{m12}(EWL - (IWL_{y,m} + \frac{P_{y,m} - E_{y,m} - LG_{y,m} + \sum_{r=1}^{r21} I_{y,m,r}}{A_{y,m}})) \quad (4)$$

where $C_{1,1}$ is the difference of Lake Urmia water level and its ecological water level (m), EWL is the ecological water level (1274.1 m), IWL is the initial water level in the lake at the beginning of each time interval (m), P is precipitation on the lake (m^3), E is evaporation from the lake surface (m^3), LG is the water loss to the groundwater (m^3), I is the water inlet of 21 rivers to the lake (m^3), A is the area of the lake (m^2), and y, m, and r represent the year, month and river, respectively.

During past years, the decline in aquifers' water levels across the Urmia Lake Basin has raised concerns about future water security. Groundwater over-abstraction caused by the growth of licensed and unlicensed wells results in increased land subsidence, energy consumption, and the intrusion of saline water into aquifers [81]. Equation (5) estimates the dependency of each alternative on the groundwater resources:

$$C_{1,2} = \frac{\sum_{y1}^{y21}\sum_{m1}^{m12} GSD_{y,m}}{\sum_{y1}^{y21}\sum_{m1}^{m12} TSD_{y,m}} \quad (5)$$

where GSD is the groundwater supply delivered (m^3), and TSD is the total supply delivered (m^3).

Since most future scenarios are energy-consuming based, CO_2 emission is another developed indicator in this study, estimated by summing annual CO_2 emission of demand and supply side. The value of this indicator is calculated by the LEAP software.

The aim of economic assessment as the second criterion is to investigate the economic efficiency of each future scenario. Two indicators that are regarded in this section are employment and the net present value (NPV). Using the first indicator, the potential of providing new job opportunities for each scenario will be estimated, and the NPV indicator compares the costs and benefits of each scenario by converting the total costs and benefits to present value to ensure effective policymaking. The calculation formula for NPV is presented in Equation (6) [82]:

$$C_{2,2} = \text{NPV} = \sum_{t=0}^{n} \frac{CF_t}{(1+d)^n} \quad (6)$$

Here, CFt is the expected net cash flow over a period of one year, D is the discount rate, n is the timespan from time now, and t is the period of time over which that cash flow occurs.

The social criterion, as the third criterion, is assessed through five indicators. The first two indicators that reflect the opinion of experts are social acceptance and governmental support. Adaptation to challenges airing after implementing the policies, especially for the farmers, is a significant problem. Effective coordination among authorities involved in water, energy, agriculture, industry, and environment sectors is crucial to overcome the social concerns and provide technical support, assessed in the second indicator. Ignoring the importance of these two social factors has caused the failure of some of the restoration plans.

The other three social indicators are developed to assess the potential of each scenario for increasing water security in each sector and are estimated according to the average annual unmet water of each sector by Equation (7):

$$C_{3,s} = WD_s = \frac{1}{n} \times \sum_{y_1}^{y_{21}} \sum_{m_1}^{m_{12}} \sum_{ds_s} (D_{y,m,ds} - S_{y,m,ds}) \quad (7)$$

where WD is water deficit (m^3), D is water demand (m^3), S is the water supply (m^3), ds is the index for demand site, and s is the index for potable water, agricultural and industrial sectors.

Technology plays an important role in developing sustainable policies. The growth of renewable energy sources, improvement of water-saving technologies for agriculture, reducing physical water loss in water distribution networks, and industrial growth all highly depend on shrinking the technological gaps. It can be considered as a major constraint for implementing policies and sustainable development. In this study, the required technical ability for each policy is determined by the opinion of experts, which relies on knowledge and experience.

2.5.2. Integrated AHP-TOPSIS Method

Different MCDA methods are developed in order to rank alternatives based on evaluation criteria. In this study, a hybrid approach is adopted, which uses the AHP for determining weights of criteria, and then ranking the alternatives is conducted by the TOPSIS method. The AHP method proposed by Saaty [83] is a well-known method for MCDA. In this method, a complex decision-making problem is considered as a hierarchical structure based on its properties. This structure includes elements and levels corresponding to the common features of the elements. The first level, intermediate levels, and lowest level correspond to the final goal, criteria, and sub-criteria, and decision alternatives, respectively. This hierarchical structure is designed so that each element at a specific level is compared with other elements at the same level in terms of relative importance. This method is scalable and can easily be implemented in the decision-making problems [84].

TOPSIS is a ranking method that was proposed and modified by Hwang and Yoon [85,86]. In a multi-dimensional computing space, this method identifies an alternative that is closest to the ideal solution and farthest from the negative ideal solution. Computational efficiency and capability to measure the relative performance for each alternative are the most important advantages of this method [87], however, it lacks an efficient procedure for assessing importance weights for attributes.

The integrated AHP-TOPSIS combines the advantages of AHP (e.g., pairwise comparisons of alternatives while eliciting weights) and TOPSIS (e.g., straightforward computations, and not suffering from capacity limits on numbers of attributes and alternatives) [88]. The AHP is used to score and set the share of the importance of the relative weights for the decision criteria-sets, and the TOPSIS method is used to obtain the final ranking. The need for precise weights, reducing the subjectivity of decisions through checking consistency ratios, breaking down complex decision-making problems into manageable steps, and large numbers of alternatives were the main reasons for employing this method in this study.

The integrated AHP-TOPSIS method is implemented in this study through eleven steps as follow: constructing the pairwise comparison matrix based on the judgments of experts using the fundamental scale of AHP presented by Saaty [89] (Table 5), constructing the normalized pairwise matrix, calculating the criteria weight vector, calculating the consistency of weights [90], assessing the inconsistency of subjective judgments of decision-makers, establishing the decision matrix, normalizing the decision matrix, constructing the weighted normalized decision matrix, determining the optimal positive and negative solutions, calculating the distances between the value inserted in the matrix by the ideal solutions, and calculating the relative closeness to the ideal solution and ranking the preference order. The details of this calculations are represented in the supplemental material.

Table 5. Scales of relative importance [89].

Saaty Scale	Linguistic Variables
1	Equally importance
3	Weakly importance
5	Essential importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermittent values between the two adjacent judgments

3. Results and Discussion

By using the explained methods, the analysis of implementing each policy scenario is discussed in this section. These policy scenarios are analyzed considering the climate change scenarios representing the external impacts influencing the studied district. Further, a ranking of policy scenarios using MCDA is presented and discussed.

3.1. Scenario Analysis Results

The policy scenarios suggested in this study are based on the different combinations of the existing solutions used to establish sustainable development in the Urmia Lake Basin. In this study, combinatorial solutions are taken into account because of two reasons. The first is that sustainable development is possible only when multilateral growth in all aspects, including economic, social, and ecological, is realized. The second reason is that ignoring one area's impacts on other areas may distort our understanding of some aspects of the policies. So, this ignorance will negatively impact the future and face the next generations with serious challenges and crises.

In this study, alterations of temperature, rainfall, and evaporation are used to modelize the impacts of two climate change scenarios on the environment, water, and energy sectors. The decline of the rainfall and an increase in temperature and evaporation will result in severe hardships in policy and decision-making in the future. Therefore, realizing all of the available potentials for solving problems becomes a necessity.

The impacts of four scenarios on energy demand, unmet water demand, and Lake Urmia water level are depicted in Figure 5. In these diagrams, results of S0 and S8 scenarios, which are considered to be the limit state of possible events, are depicted. The S0 scenario represents the BAU scenario, and the S8 scenario depicts the realization of challenging goals in different areas, according to Tables 2 and 3.

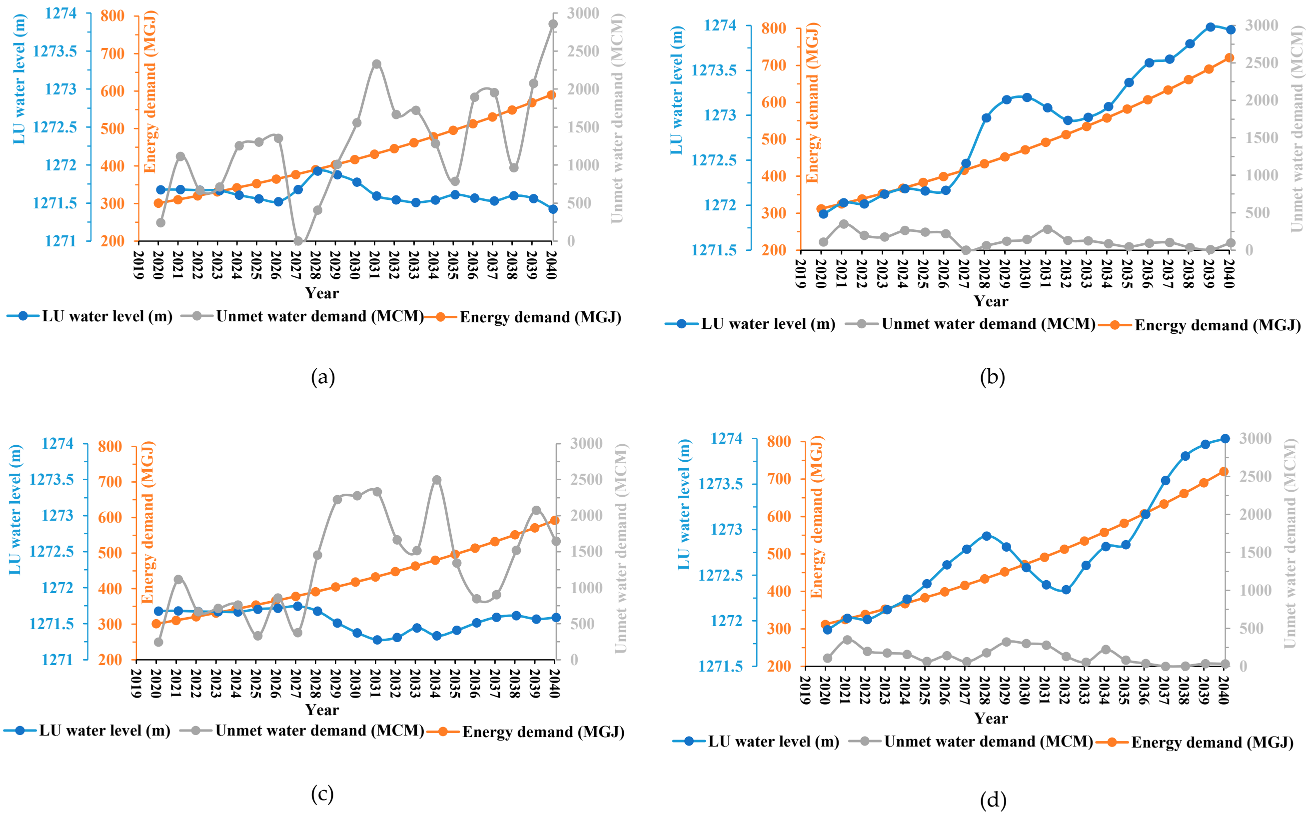

Figure 5. Overall trends in total energy demand, Lake Urmia's water level, and unmet water demand for (**a**) RCP 4.5-S0, (**b**) RCP 4.5-S8, (**c**) RCP 8.5-S0, and (**d**) RCP 8.5-S8.

In the RCP 8.5-S0 and RCP 4.5-S0 scenarios, the Lake Urmia water level will decrease slightly compared to the current situation. This decrease would be considered an ecological crisis, and so it is necessary to prevent it. In some years (such as 2028 and 2029 in the RCP 4.5 scenario), the increase in rainfall will have a time-limited impact on the lake's water level. The average water level is 1271.4 and 1271.2 m for RCP 4.5 and RCP 8.5, respectively. Bakhshianlamouki et al. [19] in their study on the Urmia Lake Basin have developed a system dynamics model to simulate the water-energy-food nexus. The impacts of implementing restoration plans by considering three climate change scenarios (RCP 2.6, RCP 4.5, and RCP 8.5) have been evaluated in their study. They reported that in case the BAU scenario is followed, there will be a slight decrease in the Lake Urmia water level for all three climate change scenarios. In addition, they indicated that rainfall fluctuations have a major impact on the lake's water level, and in 2040 it reaches 1271.4 with a slight difference in three scenarios. These results are in line with the findings of the current study.

In the S8 scenario, the Lake Urmia water level increases in the horizon of both climate scenarios. In the year 2040, it will be equal to 1274 m, which is very close to the lake's ecological water level (1274.1 m). This increase shows that reaching the ecological level is only possible when all challenging goals are pursued concurrently, multilateral, and strictly targeted. In this scenario, the increase in rainfall in some years in both climate scenarios is an opportunity to increase the lake's water level. In addition, continuous persuasion for conducting solutions that reduce water demand in different areas (especially agriculture) will result in a situation in which the lake's ecological water demand would be met. In both RCP 4.5-S8 and RCP 8.5-S8 scenarios, rainfall and evaporation fluctuations have resulted in the fluctuation of the lake's water level, occasionally. However, in the long term, conducting sustainable development solutions has led to getting close to the ecological water level in both scenarios, which indicates suitable adaptation of these solutions with different climate conditions.

There is a remarkable difference in unmet water demand between S0 and S8. In scenario S0, the studied district is very vulnerable to supplying the water demand because of the rainfall fluctuations. In some years, failure in supplying water demand will lead to social conflicts, and, consequently, water security faces numerous risks. The annual unmet water demand average is equal to 1262 million cubic meters (MCM) and 1292MCM in RCP 4.5-S0 and RCP 4.5-S0, respectively. In both climate scenarios, the unmet water demand increases; however, the slope of this increase in RCP 8.5 is more than RCP 4.5.

In the S8 scenario, the quantity of water demand decreases and is managed during consecutive years by implementing different strategies. This observation indicates the remarkable importance of efficiency improvement strategies. In addition, water security in both climate scenarios is obtained satisfactorily.

Another subject that can be analyzed by this figure is the alterations in energy demand. According to this diagram, in 2040, energy demand in the RCP 8.5 scenario will be 0.5% more in comparison to the RCP 4.5 scenario. The most crucial factor in this increase is the rise of the temperature, which will increase energy demand in the warm months of the year. In addition, in 2040, the energy demand in the RCP 4.5-S8 scenario will increase by 22% compared to the RCP 4.5-S0 scenario. The reason is the dependence of suggested strategies on energy. The increase in energy demand in agriculture and industry sectors results in increased productivity and development. On the other hand, this increase in electricity demand can lead to an increase in GHG emissions. To prevent this from happening, it is necessary to realize the potential of renewable energies in both domestic and power plant applications to achieve sustainable development in all areas.

What is explained in this section is the limit states that may happen in the studied district. The status of other scenarios and values related to the diagrams of Lake Urmia water level, energy consumption, and unmet water demand in each climate scenario will be situated between the S0 and S8 diagrams.

3.2. Criteria Weights

The 11 indicators representing four criteria classes, including environmental sustainability, economic development, social development, and technical development, are assessed by decision-makers who are experts in the fields of agriculture and food, environment, social service, energy, water resources, and economy. These experts are from local and national governments with an academia and practice background. All of them are among the leaders tackling the challenges associated with this district.

The decision-makers' preferences are represented in Figure 6. According to the results, there is an agreement between stakeholders about the importance of some indicators (e.g., NPV), but their judgment varies for some other indicators (e.g., social acceptance). The provision of potable water and increasing the Lake Urmia water level are the two most important indicators, while CO_2 emission and NPV are considered among the two least important ones. The mean value of the weight of indicators is 0.09, and the standard deviation is 0.021. According to the decision-makers' priorities and preferences, CO_2 emission does not play a crucial role in future sustainable development, as does Lake Urmia's water level and groundwater storage. The role of social acceptance is underestimated by most groups. However, the maximum score value is attributed to this indicator by social service experts. The consistency ratio of all pairwise comparisons matrix was below 0.10, with an average of 0.03, which confirms the consistency of the decisions.

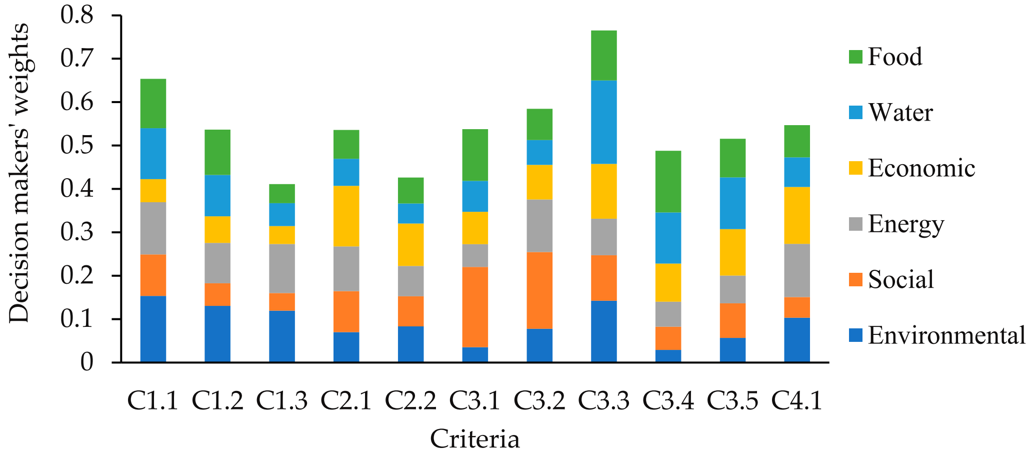

Figure 6. Decision-makers' weight tradeoffs between indicators.

3.3. MCDA Result

After constructing the pairwise comparison matrix, the TOPSIS method is used for determining the relative closeness of each scenario to the ideal solution. Then the ranking of each scenario will emerge. Figure 7 depicts the result of ranking different scenarios in different fields and for different climate scenarios. Based on this figure, it could be understood that there is a proper consensus between experts in different fields about the best solution for grounding sustainable development. The formation of this consensus could justify constructing the pairwise comparison matrix, which is based on the average values assigned for each matrix element by different experts. Figure 8 illustrates each scenario's relative closeness to the ideal solution after using the new pairwise comparison matrix.

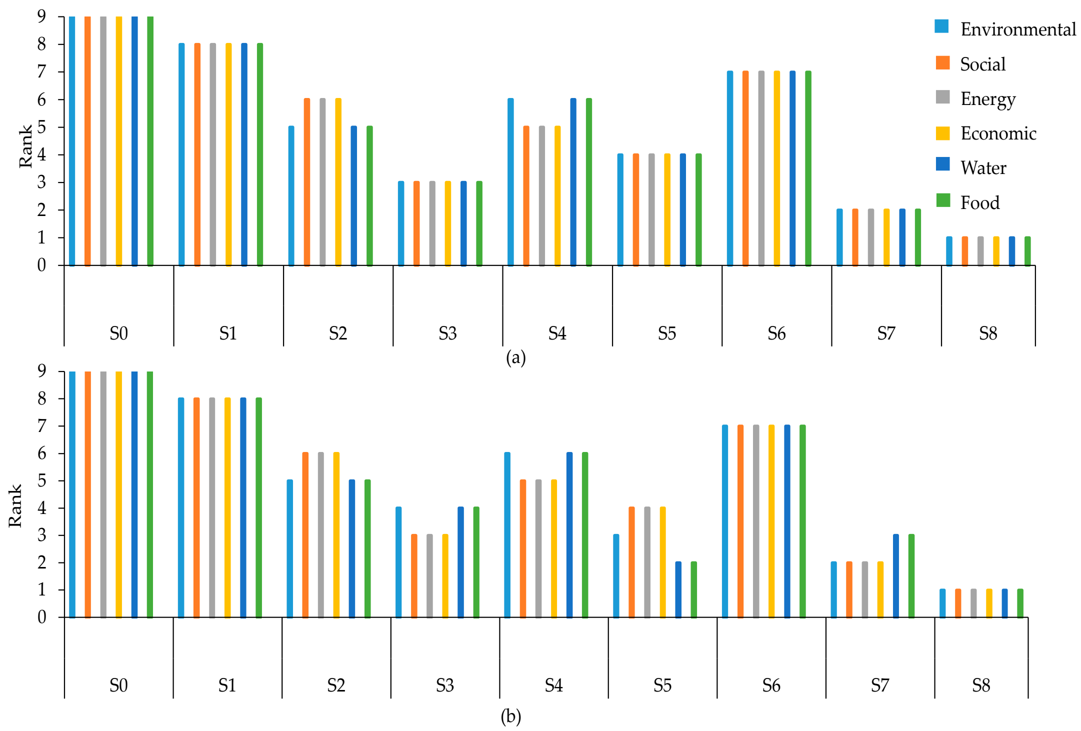

Figure 7. Ranking of alternatives by TOPSIS method according to six decision-makers' weight for (**a**) RCP 4.5 and (**b**) RCP 8.5.

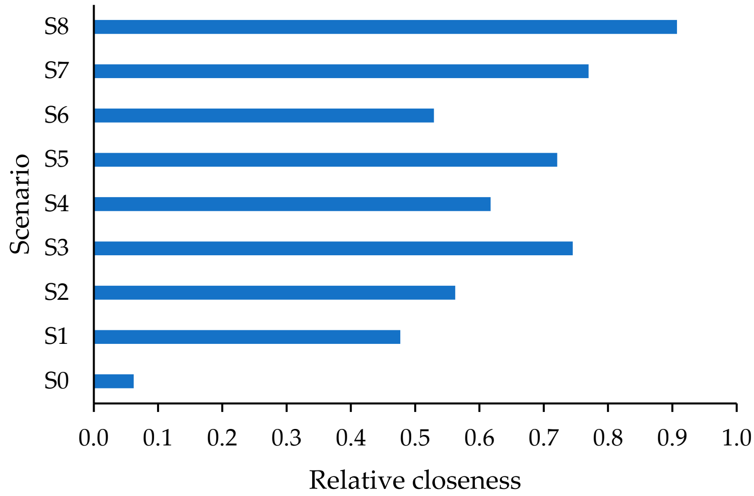

Figure 8. The relative closeness of each scenario to the ideal solution.

As expected, the S8 scenario, which has strict targeting for development, is ranked first. Social acceptance, governmental support, and technical ability are the hardest challenges in implementing this scenario. Comprehensive reform in agricultural structures, industrial development, promotion of renewable energies, and supplying infrastructure needed for reducing water loss in water distribution networks need long-term and constant investment, reducing investment risks and upgrading technical ability. Therefore, this scenario is the ideal available option for moving toward sustainable development in this district, but it is accompanied by crucial social and political problems in solving them. So, the realization of this scenario seems to face complicated challenges. Because of these impediments, we can see in Figure 8 that the relative closeness of this scenario to the ideal solution is equal to 0.9. The reason for the difference from 1 is the difficulty of solving the existing challenges for operationalizing this scenario's targets.

After S8, there is a consensus on the second, third, and fourth options in the RCP 4.5 scenario. There is no such consensus for these options in the RCP 8.5 scenario. The common thing between these scenarios is the necessity of implementing challenging goals in the industry sector. Industry growth and structural adjustment are pursued in this strategy. The centrality of pursuing the challenging goals in the industry field in all of these three scenarios demonstrates the importance of this solution for moving toward sustainable development in this district. According to Figure 8, it could be inferred that the relative closeness of these scenarios to the ideal solution is very similar to each other, with an average value of 0.75. Implementing this policy scenario has the merit of being more socially acceptable in the agricultural sector. Achieving the industrial sector's challenging goals has more influence on grounding sustainable development compared to the challenging goals of the potable water, energy, and agriculture sectors. In addition, as a replacement for part of the agricultural sector to handle GDP, it has beneficence in increasing the efficiency of water consumption. As a result, Lake Urmia's water level and groundwater level could increase.

According to Figure 8, S7 is the closest scenario to the ideal solution, in which the challenging goals of the energy and economy sectors and moderate goals of the potable water and agricultural sectors are pursued. The essential reason is that the proposed policies in industrial and agricultural sectors will have a great impact on the future energy demand and, as a result, constructing the required infrastructure for meeting the demand and also using the opportunity of renewable energies to reduce GHG emission become necessary. Pursuing challenging goals in agricultural and potable water sectors, alongside the industry sector, places S3 and S5 scenarios in the third and fourth rank.

According to Figure 7, there is a disagreement in both climate change scenarios about S2 and S4 for the fifth and sixth rankings. The main reason that experts in water, food, and environment fields do not agree with other experts in the economy, energy, and social services is the unmet water demand in different sectors, varying from one scenario to another.

The achievement of challenging goals in the potable water sector is the common strategy in both scenarios. The average of their closeness to the ideal solution is equal to 0.59.

S6 is ranked seventh with experts' consensus. In this scenario, energy and agricultural sector strategies are pursued strictly, and industry and potable water strategies are pursued moderately. The relative closeness of this scenario to the ideal solution is 0.53, according to the results of the TOPSIS model.

Based on these results, it can be expressed that, for achieving sustainable development and also because of the necessity of choosing particular sectors for more investment and efforts, the achievement of challenging goals in the industry sector has the maximum of importance and necessity, while the agricultural sector has the minimum of importance.

S1 scenario, in which all of the strategies are pursued moderately, is ranked 8th as expected, and its relative closeness to the ideal solution is equal to 0.48. The critical point about the S1 scenario is the considerable difference between this scenario's relative closeness and the S0 scenario's to the ideal solution. It means that implementing targets of different sectors, even moderately, can improve the current situation considerably. The relative closeness of the S0 scenario to the ideal solution is 0.06, which means that we will face a fatal situation in the future in the case of insisting on the same policies. So, it can be said that the continuity of the conditions that have led to the current situation will bring about numerous sufferings in different sectors. As a result, policymakers should do their best to pursue different targets and change the current conditions.

The last point we can deduce from Figure 7 is the lack of difference between climate scenarios about the priority of available solutions. However, according to the severe condition of rainfall decrease in the long term for the RCP 8.5 scenario, employing solutions for adapting to the occurred condition will be more necessary for policymakers.

4. Conclusions

In this study, a complicated set of relations between different sections of Urmia Lake Basin is analyzed using the WEFE nexus and MCDA approaches. In addition, considering the uncertainties of climate change and the possible future policies, there has been an effort to compose specific strategies for the sustainable development of the Urmia Lake Basin. This water resources system is of high sensitivity because of Lake Urmia. The exact modeling of different sectors has provided the possibility of holistic and concurrent analysis of the impacts of different strategies in agriculture, industry, potable water, and energy on sustainable development processes in the district. Views of experts of energy, social services, water, economy, food, and environment are used to determine the best combination of strategies and the impact of different scenarios. The results are as follows:

1. Lake Urmia's water level is the most environmentally vulnerable measure in the Urmia Lake Basin district, and its ecological level is only achieved when challenging goals in different fields are pursued. To operationalize this target, it is necessary that the government carry out multilateral supports that will help to decrease the investment risk and increase technical ability. In addition, implementing reforms in agriculture, such as decreasing cultivated land and modifying cultivation patterns, will be faced with social resistance, which will need to be addressed.
2. The main distinction between different climate scenarios is rainfall fluctuations during different years. In addition, it can be expressed that temperature and evaporation increase and a decrease in rainfall are more severe in RCP 8.5 than RCP 4.5.
3. Implementing sustainable development solutions in the studied district will result in a 211% increase in energy demand in the agriculture and industry field until 2040. Consumption of this amount of energy will lead to an increase in releasing GHG in the Urmia Lake Basin. In order to prevent this pollution, realizing the potential of renewable energies is a necessity.

4. After summing up the views of experts in different fields, it could be said that the most important measures for evaluating possible strategies in Urmia Lake Basin are supplying sustainable drinking water and increasing Lake Urmia's water level.
5. Because of the necessity of the holistic development of all sectors, scenarios with various combinations of each field's targets were taken into account. According to MCDA results, the current situation's continuity will result in severe economic, ecological, and social sufferings in the district. As expected, pursuing challenging goals in all sectors is the closest scenario to the ideal solution. However, the possibility of implementing this scenario is fragile because of the social and political challenges. Pursuing challenging goals for industry growth and industry structure adjustment will have more effectiveness compared to other sectors. Following challenging goals is of minimum importance in the agricultural sector.

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Nomenclature

Symbols

A	Activity level
AWD	Agricultural water deficit (m^3)
D	Demand
d	Discount rate
E	Evaporation (m^3 $month^{-1}$)
EF	Emission factor (Tones CO_2-eq)
GSD	Groundwater supply delivered (m^3)
I	Inlet (m^3 $month^{-1}$)
IS	Initial Storage (m^3)
IWD	Industrial water deficit (m^3)
LG	Loss to groundwater (m^3 $month^{-1}$)
LWL	Lake water level (m^3 $month^{-1}$)
MWD	Potable water deficit (m^3)
n	Timespan from time now
NPV	Net present value (million USD)
P	Precipitation (m^3 $month^{-1}$)
S	Supply
TSD	Total supply delivered
WD	Water deficit (m^3)
WSV	Water storage volume (m^3)

Subscripts and superscripts	
ds	Demand site
g	Gas
m	Month
r	River
s	Site
t	Time
y	Year
Abbreviations	
AHP	Analytic hierarchy process
BAU	Business as usual
CORDEX	Coordinated regional downscaling experiment
GHG	Greenhouse gas
IPCC	Intergovernmental panel on climate change
LEAP	Low emissions analysis platform
MCDA	Multiple criteria decision analysis
MCM	Million cubic meters
MGJ	Million gigajoules
RCP	Representative concentration pathway
SDG	Sustainable development goal
SEI	Stockholm environmental institute
TED	Technology and environmental database
TOPSIS	Technique for order of preference by similarity to ideal solution
ULRP	Urmia lake restoration program
WEAP	Water evaluation and planning system
WEF	Water-energy-food
WEFE	Water-energy-food-environment

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