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Indicator-Based Evaluation of Türkiye's Water–Energy–Food Nexus Profile for Sustainable Development

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ABSTRACT
The Water–Energy–Food (WEF) Nexus rests on the reality that interlinkages among resources are mutually interdependent; changes in one sector can have significant repercussions in the others. To this end, several methods, models, and tools are being developed to analyze interconnections, to measure resource use, and to develop integrated policies. In this study, the WEF Nexus concept and its component interactions are examined using a nexus framework and flow diagrams based on WEF resources. Türkiye's water and energy resources, food production, climatic conditions, and greenhouse gas emissions are presented in depth, drawing on up-to-date data sources. The WEF Nexus Index and its outputs for Türkiye over 2019–2023 are compared at both global and OECD scales. The WEF Nexus Index is a composite indicator that evaluates national resource performance by combining 21 equally weighted parameters across water, energy, and food. Official WEF Nexus Index data are used to assess Türkiye's global position among 181 countries. By accounting for "access" and "availability" dimensions for each resource, the index enables indicators to be evaluated on a 0–100 scale. For 2023, Türkiye's WEF Nexus Index stands at 56.6, while the water, energy, and food sub-indices are 58.5, 44.0, and 67.3, respectively. Türkiye ranked 67th among 181 countries in 2019 and 90th in 2023. Over the five years, Türkiye's average WEF Index is 58.7; sub-index averages are 65.2 for water, 44.9 for energy, and 65.8 for food. It has exhibited relatively low performance, particularly in energy. Within the WEF Nexus, availability scores of 45.5 for water, 19.5 for energy, and 58.4 for food negatively affect sustainable development. Taken together, these results indicate that to ensure balanced resource use and national food security, Türkiye must manage its limited water resources accurately and efficiently, and adopt environmentally sensitive, renewable energy-oriented, and coherent policies.

Keywords: WEF Nexus, Composite indicators, SDGs, Policy, Türkiye Perspective, OECD

1. Introduction

Given the complex interlinkages among water availability, energy supply, and food production at regional, national, and global scales, Water–Energy–Food (WEF) balances often deteriorate in negative ways, with multifaceted implications for sustainable development and economic growth. Accordingly, the WEF Nexus was first discussed by Hoff in 2011 at the World Economic Forum in Bonn to highlight issues of resource security (Hoff 2011). Rather than a single-sector perspective, the WEF Nexus points to the need to understand the intrinsic connections among water, energy, and food systems, recognizing that changes in one sector can produce significant effects in the others (Daher & Mohtar 2015; Al-Saidi & Elagib 2017; Liu et al. 2018).

The WEF Nexus approach focuses on maximizing total benefits across the three sectors and delivering sustainable solutions (Wu et al. 2021; Li et al. 2025; Yang et al. 2025). This perspective supports the coordination of policies that promote fairer and more efficient resource use and the translation of management strategies into practice.

Worldwide, numerous scientific studies on WEF Nexus issues are conducted at different scales. Albrecht et al. (2018), in a systematic review of 245 studies on the WEF Nexus, found that current methods are generally insufficient in reflecting interdisciplinary interactions and social dimensions. The study reveals that most analyses rely solely on quantitative methods and are confined within disciplinary silos. The authors argue that to overcome these problems and solve resource management challenges, interdisciplinary and mixed-method approaches involving stakeholder participation must be developed.

David et al. (2024) analyzed the impact of economic indicators on the sustainability of the WEF Nexus using Structural Equation Modeling (SEM) in a quantitative study conducted with 282 managers in South Africa. As a result of the research, resource pricing mechanisms, employment rates in the sector, imports, and exports were determined to be four key economic factors affecting resource security. The study emphasizes the need to consider the economic power of the public for sustainable WEF management and the importance of strategic investments based on comparative advantages.

Eriksson et al. (2025), in a Delphi study conducted with 70 international experts, determined that the focus of WEF Nexus research has shifted from mere resource security towards governance and ecosystem services. However, the study reveals that existing methodologies have failed to keep up with this conceptual shift, remaining largely limited to mapping inter-resource linkages, which hinders policy development processes. The authors suggest that for the field to advance, methods need to be updated to include governance and ethical dimensions.

Farmandeh et al. (2024), in their mixed-method research examining the scope and methodology of WEF Nexus studies, determined that the primary focus of these studies is "system sustainability assessment". The research reveals that WEF studies are gathered in seven main areas and that simulation and statistical analyses stand out as the most effective techniques methodologically. The authors propose a decision diagram to guide researchers in selecting the most optimal method suitable for their study objectives.

Li et al. (2025), in a systematic review examining 834 studies, evaluated the success of WEF Nexus research in quantifying resource interactions through a distinction between theoretical and empirical studies. The research reveals that despite the increase in literature, the scope of resource interactions addressed since 2011 has not expanded, and empirical studies have lagged behind theoretical models, containing methodological inconsistencies. The authors emphasize that to achieve the Sustainable Development Goals (SDG 2, 6, and 7), methodologies that go beyond physical interactions and are more compatible with research questions need to be developed.

Liu et al. (2018) present a special issue aiming for the integrated management of these resources for sustainable development by addressing the complex linkages between energy, water, and food (EWF). Emphasizing the necessity of an interdisciplinary "nexus" approach in the face of increasing global demands and resource constraints, the study examines 24 papers gathered under four main headings: trends, governance, clean energy technologies, and implementation examples. This review paves the way for the development of integrated policies and strategies by ensuring a better understanding of cross-sectoral trade-offs and linkages.

Mondal et al. (2025), in a comprehensive review of 770 articles examining interdependencies in the WEF Nexus for a sustainable agricultural future, analyzed the limitations of the concept in practical application and deficiencies in policy formulation. Presenting three original conceptual frameworks addressing cross-sectoral interaction and complexity in agricultural production, the study emphasizes that interdisciplinary collaboration is critical to achieving sustainability goals. The authors suggest that future research should focus on strengthening governance frameworks and deepening the interface between WEF and agricultural policies.

Wu et al. (2021) analyzed the supply and demand sides of water-energy-food systems with a holistic approach using the System Dynamics-based WEF-Sask model developed for the Saskatchewan region of Canada. As a result of the study, it was determined that while increasing wind energy capacity created synergy by reducing water demand and emissions, irrigation and biofuel expansion caused significant trade-offs between food production, hydroelectric production, and food exports. The authors emphasize that this model structure allows for scenario analyses for integrated resource management and is adaptable to different regions.

Yang et al. (2025) analyzed the sustainability of the WEF system using a new assessment framework based on a "pressure-support" perspective integrated with Sustainable Development Goals (SDG 2, 6, and 7) in the case of the Yellow River Basin. The study reveals that although the sustainability index in the basin has increased over time, the system generally remains under pressure and in an unsustainable state, and furthermore, eastern regions perform better than the west. The authors determined that infrastructure, environmental regulations, and technological progress make significant contributions to the system, whereas urbanization has an inhibitory effect on sustainability.

Yupanqui et al. (2025), in their study examining the historical evolution of the WEF Nexus and its relationship with Sustainable Development Goals, critically evaluated existing frameworks, modeling tools, and gaps created by nature-driven crises such as water scarcity. The study proposes an integrated "WEF security index" and a new business model aimed at quantifying country-based resource management, covering disaster risk, climate change, and trade trade-offs, based on internationally accepted metrics. The authors state that this proposed platform will create a strategic roadmap to contribute especially to SDG 2, 6, 7, 8, and 13 targets.

Zhang et al. (2018), in a comprehensive review on the WEF Nexus, compared conceptual definitions and classified research questions into three main themes: internal relationships, external impacts, and system evaluation. The study guides researchers on appropriate method selection by analyzing the advantages and disadvantages of eight different modeling approaches. The authors emphasize that future challenges such as determining system boundaries, data uncertainty, and resolving underlying mechanisms must be overcome for the development of the field.

Zhang et al. (2020) developed an integrated assessment and optimization model based on synergy theory, information entropy, and genetic algorithms to quantitatively analyze synergies in WEF systems in a study applied in the China case. Research results

determined that water supply is the most critical factor for system stability, while revealing that renewable energy development and integrated irrigation methods steer the system toward a stable equilibrium state by reducing water conflicts.

The Food and Agriculture Organization of the United Nations (FAO) has noted that adopting a WEF Nexus perspective can support food security and foster sustainable agricultural development (FAO 2014). The International Renewable Energy Agency (IRENA) has similarly highlighted that renewable energy solutions can help mitigate certain mismatches across water, energy, and food systems, delivering significant advantages for all three sectors (IRENA 2015).

Current research centers on examining the internal linkages among water, energy, and food systems, understanding their complex interactions (Eriksson et al. 2025), and analyzing them (Yang et al. 2025). In practical terms, the Nexus perspective signals the need for more integrated and coordinated management of natural resources across sectors and scales (Daher & Mohtar 2015). On the other hand, the status of the three resources can be influenced in multiple ways by factors such as climate change (Gao et al. 2024), population dynamics and land use (Imasiku & Ntagwirumugara 2019), and regional and national strategies and policies (Alzaabi & Mezher 2021).

Degirmencioglu et al. (2019) evaluated the sustainability of the agricultural production system in the Gediz Basin of Türkiye using the WEF axis approach and developed future scenarios including climate change, urbanization, and technological developments. The study reveals that land loss due to urbanization and water scarcity resulting from climate change are inevitable. The authors emphasize that the selection of drought-resistant species and the adoption of modern energy and water-saving practices such as direct seeding and drip irrigation are necessary for the sustainability of agricultural production.

Özgür (2025), in her doctoral dissertation conducted using the Konya Closed Basin as an example, examined the integration of the WFE axis approach into planning and governance processes through a hierarchical analysis encompassing national, basin, and regional scales. The research reveals a need for a flexible paradigm shift in the current planning system to increase inter-sectoral synergies and reduce trade-offs. Considering these multi-layered assessments, the author offers integrated and sustainable policy recommendations for Türkiye's resource management.

The Nexus perspective supports how resources should be used jointly at national or regional levels, how they can be managed more effectively, and the processes of cost-effective planning, decision-making, implementation, monitoring, and evaluation. In this study, the WEF Nexus concept is operationalized, and mutual interactions are examined using a nexus framework and flow diagrams based on WEF resources. Türkiye’s water and energy resources, food production, climatic conditions, and greenhouse gas emissions are presented in depth using up-to-date data sources.

A review of the existing literature reveals that studies on the WEF Nexus in Türkiye are largely limited to regional analyses, such as basin-based analyses, or focus on individual sectors. This study fills a significant gap in the literature by being one of the first comprehensive studies to evaluate Türkiye's WEF Nexus profile at the national level using a composite indicator approach. The original value of the study lies in presenting Türkiye's resource security performance during the 2019-2023 period, not only internally but also from a comparative (benchmarking) perspective with global and OECD averages. Furthermore, this research analyzes Türkiye's WEF security by disaggregating it into 'Access' and 'Availability' sub-dimensions; thus, it aims to present a holistic and macro-level roadmap for policymakers by revealing the critical imbalance between the country's infrastructural achievements and physical resource constraints with internationally validated, concrete data.

2. Conceptual Nexus framework

WEF Nexus approach is explained from a systems perspective by integrating it with the Sustainable Development Goals (SDG-2, SDG-6, and SDG-7), as shown in Figure 1 (Dansie et al. 2024). The diagram sets out the mutual interdependencies among water, energy, and food systems through supply, demand, and stocks, placing people, landscapes, and ecosystems at the center to emphasize the socio-ecological context of the cycle. While water is a fundamental input for energy generation and food production, energy is required to provide clean water. Energy production processes, in turn, exert direct effects on the quality and quantity of water. Similarly, food systems are highly dependent on both energy and water, and agricultural production, land use and water infrastructure, fish production, and ecosystems are all affected. Energy security, food security, and water security are positioned as the three principal “entry points” at the heart of governance, policy, and investment processes within this cycle.

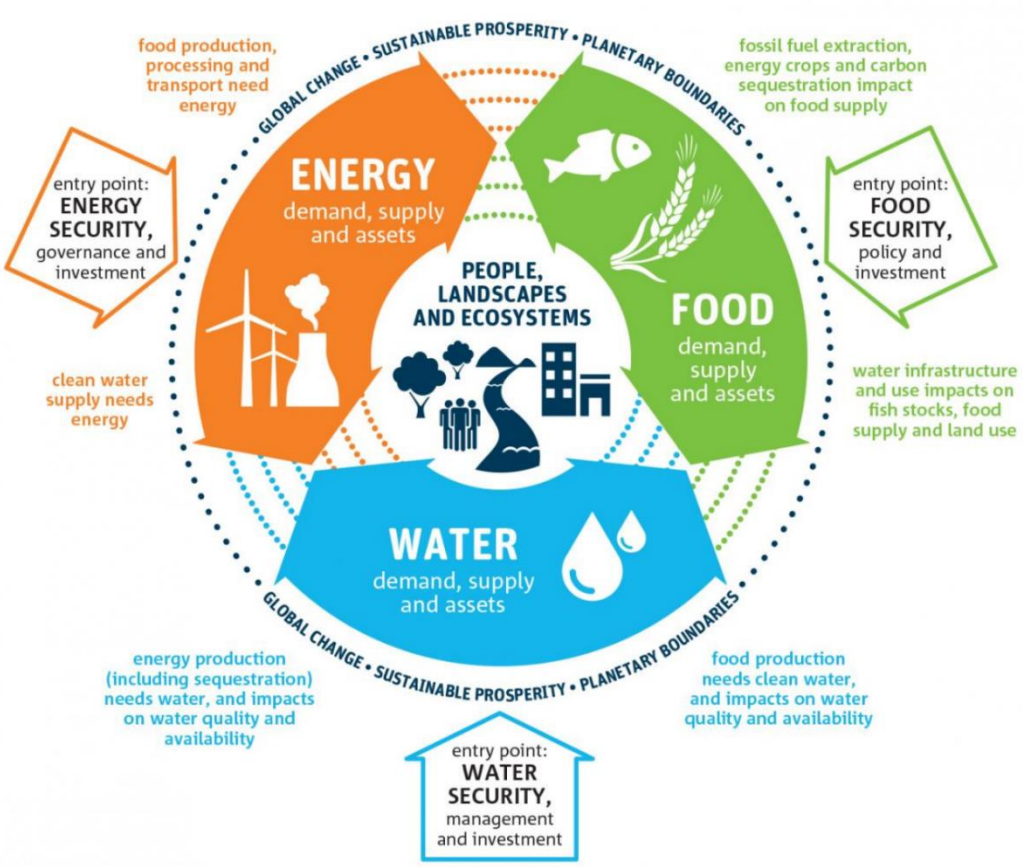


Figure 1- Conceptual framework of WEF Nexus (Dansie et al. 2024)

According to UN-Water (2013), water security encompasses the ability of a society to ensure reliable and sustainable access to water of sufficient quality and quantity. This access is fundamental not only for supporting livelihoods, human health, and socio-economic progress but also for preserving ecosystems and mitigating risks associated with water-related hazards, all within a politically stable environment.

Energy security is defined as "access to clean, reliable, affordable, and uninterrupted energy services for cooking, heating, lighting, communications, and productive uses, with due regard for environmental concerns". Energy is regarded as a cornerstone of sustainable development and a driver of economic growth (IEA 2015; UN 2015).

Food security is defined as "access to sufficient, safe, nutritious, and healthy food that meets dietary needs and food preferences for an active and healthy life" (FAO 2014). Food production -from farm to fork, encompassing plant, animal, and aquatic products- cannot be achieved without adequate and necessary water and energy resources. No living species or ecosystem, including humans, plants, and animals, can survive without water. Water is indispensable for meeting basic human needs, supporting social and economic progress, and sustaining ecosystems. Consequently, water is the primary resource at the core of agricultural, industrial, and energy production.

2.1 Water systems

A "water system" supplies both energy production facilities and agricultural production through processes involving surface water, groundwater, seawater, and wastewater treatment. The concept of water resources encompasses the total volume of accessible freshwater contained within surface bodies-such as lakes, rivers, and streams-and groundwater aquifers. The calculation of renewable water resources involves aggregating internal flows (derived from precipitation less actual evapotranspiration) with external transboundary inflows. While climatic regimes primarily dictate freshwater availability, external inflows also play a determinant role. Consequently, freshwater availability per capita is widely recognized as a pivotal metric for evaluating the sustainability of water resource management (Eurostat 2025). Within the Nexus, the dynamic nature of water systems, and their interconnections and interactions with climate, energy, land use, and economic sectors, is depicted in Figure 2 (González-Rosell Barriga 2023).

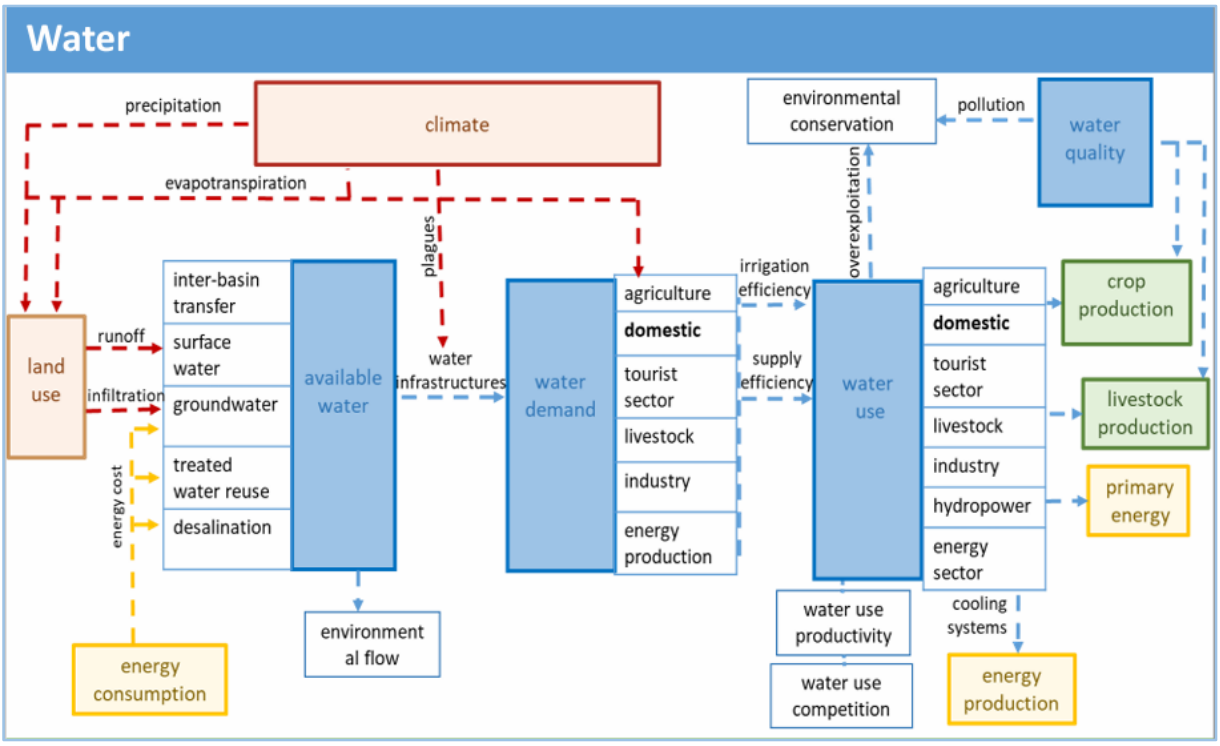


Figure 2- Water systems and components in WEF Nexus, modified from González-Rosell Barriga (2023)

In the diagram, the "available water" component comprises sources such as surface and groundwater, inter-basin transfers, water reuse after treatment, and desalination; these sources are supported by infrastructures that are directly linked to energy consumption. Water demand has a multi-sectoral structure, including agriculture, industry, energy generation, tourism, and household use. Depending on irrigation and supply efficiency, this demand translates into water use; overuse leads to both deterioration in water quality and disruption of ecosystem balance. Climate change constrains water supply by affecting precipitation, pest outbreaks, and evaporation; meanwhile, changes in land use influence the water cycle through runoff and infiltration processes. At the same time, energy production and cooling systems increase water use, while rising energy costs elevate the economic value of water. Degradation in water quality triggers knock-on effects on agricultural productivity, livestock production, and energy generation. Water is not merely a physical resource; it is a decisive system component for energy security, food production, and environmental sustainability (David et al. 2024). In sum, integrated water-management strategies planned in harmony with climate and energy policies are critical to achieving balance across the water–energy–food–ecosystem nexus (Cansino-Loeza 2022).

In agricultural contexts, water is predominantly utilized for irrigation, deriving largely from rainfall or extracted from surface and subterranean reserves through conveyance infrastructure like canals and pipes. As the leading user of both blue (surface/ground) and green (rain) water resources, agricultural output is intrinsically tied to issues of water scarcity (Hoekstra & Mekonnen 2012). Within this framework, consumption is defined as the volume of water withdrawn that is not restored to its original hydrological basin (Hoekstra et al., 2011). Recent data from the United Nations indicates that the agricultural sector is responsible for 72% of global freshwater withdrawals, significantly surpassing the industrial (16%) and municipal (12%) sectors (UN-Water 2025).

2.2 Energy systems

Because all stages of agricultural production are mechanized, the energy demand is increasing day by day. While energy is vital for achieving economic development, it is also a critical input and an integral component of the agri-food sector from farm to fork, encompassing agricultural mechanization, food-processing operations, transportation, and storage. The mutual interactions of the energy system, with water, land use, agricultural production, and climate, across the entire chain from resource provision to final consumption are presented systematically in Figure 3 (González-Rosell Barriga 2023).

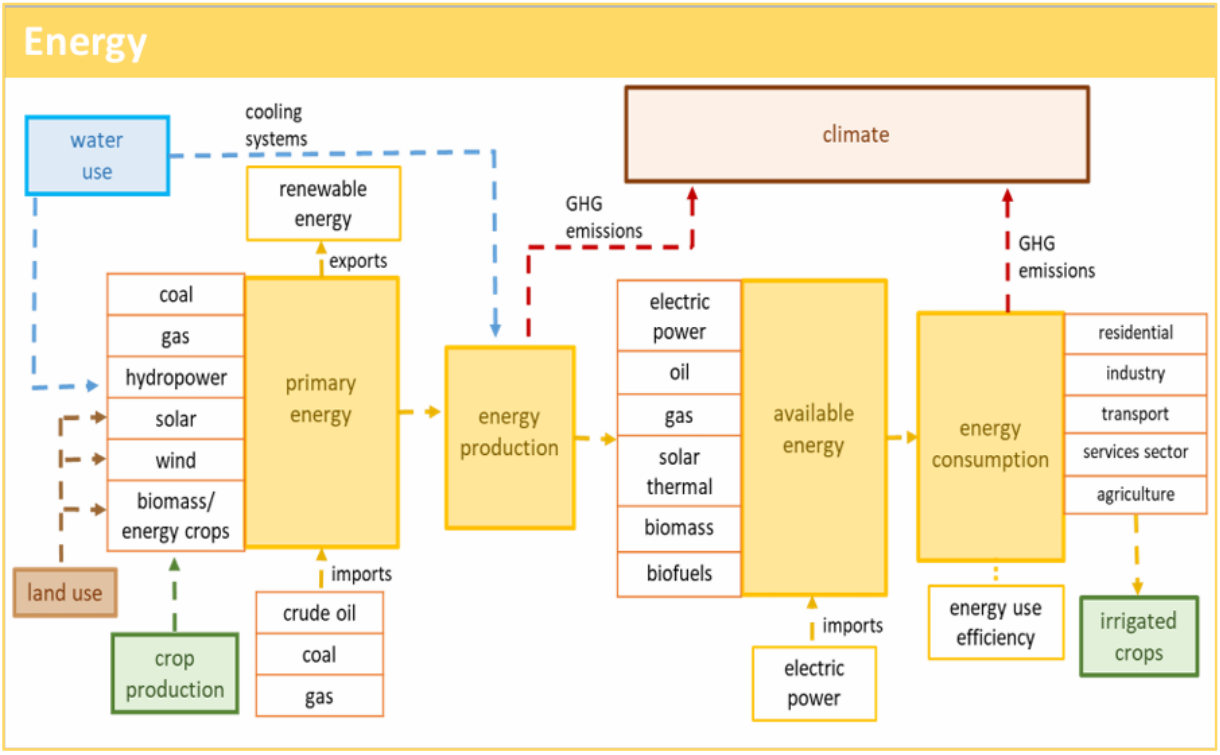


Figure 3- Energy systems and components in WEF Nexus, modified from González-Rosell Barriga (2023)

Primary energy is obtained from sources such as coal, natural gas, hydropower, solar, wind, and biomass -some of which are supplemented by imports. Water use during power generation-particularly through cooling systems-represents a critical dimension of the energy-water interaction; meanwhile, renewable energy sources such as hydropower and biomass are directly dependent on the natural water cycle (Cansino-Loeza 2022; David et al. 2024). At the same time, land use and agricultural production contribute to energy supply via energy crops and biomass production, thereby strengthening the agriculture–energy linkage. The energy produced is transferred to economic sectors (industry, transport, services, residential, and agriculture) as usable energy in the forms of electricity, petroleum, gas, solar, thermal energy, biomass, and biofuels.

The WEF Nexus approach aims to minimize trade-offs between resources, while utilizing agricultural waste in energy production presents a strategic opportunity. In this context, Ertuğrul et al. (2024), in their study conducted in south-central Texas, analyzed the bioenergy potential of agricultural waste from a WEF Nexus perspective. The study emphasizes that utilizing existing agricultural waste (especially corn, cotton, and sorghum) creates a more sustainable 'Food for Energy' model, instead of growing energy crops that create water and land competition for food production. The research findings revealed that agricultural waste in the region has an average annual energy potential of 19.27 PJ, which could replace 16% of non-renewable electricity generation in Texas. This approach constitutes a concrete example of diversifying the energy portfolio and ensuring circularity in agricultural systems without jeopardizing food security.

The process of energy consumption drives climate change through greenhouse gas emissions, which in turn directly affects both the efficiency of energy production and the level of demand. The energy system is not only an economic subsystem but also an ecological one; therefore, sustainable energy policies must be addressed in an integrated manner with water management, climate strategies, and agricultural production planning. This holistic structure clearly reveals how the energy sector operates at a system level within the WEF Nexus approach (Herrera-Franco et al. 2023; Rai 2023; Gao et al. 2024).

Throughout all stages of the agri-food chain, energy is required both directly (for tillage, hoeing, fertilization, spraying, irrigation, harvesting, and other mechanized operations) and indirectly (to produce fertilizers, agrochemicals, and machinery). Energy is consumed during primary production as well as in secondary activities such as heating, cooling, storage, drying, freezing, processing, packaging, transportation, and distribution (IRENA & FAO 2021). Various strands of the literature indicate that global food systems consume approximately 200 EJ of energy per year (Ladha-Sabur et al. 2019; Sovacool et al. 2021; Szymańska & Mroczek 2023; Corigliano et al. 2025).

2.3 Food systems

The food system is a sector characterized by environmental impacts due to the intensive use of land and water resources and pollutant emissions, arising from the use of diverse inputs (tools, machinery, equipment, energy, labor, water, fertilizers, and pesticides) during the production of crops, livestock, and aquatic products on agricultural lands (Ritchie et al. 2022). In other

words, the food system is defined as a highly interconnected network encompassing human activities related to the production, cultivation, storage, processing, transportation, marketing, and distribution of food, from farmers and producers to consumers, and it is shaped by social, economic, environmental, and political factors (Hawkes & Parsons 2019).

Degirmencioglu et al. (2019), focusing on the Gediz Basin in Türkiye, evaluated the sustainability of the agricultural production system using the WEF axis approach, considering the food system not only as an agricultural output but also as a primary consumer of water and energy resources and a determinant of food security. The study covers 26 districts in the Gediz Basin and focuses on the top 15 crops (wheat, maize, cotton, grapes, olives, etc.) that use 86.3% of the total land and 79.4% of the water in the basin. The food system analysis calculated the water footprint (blue and green water) and energy intensity (fertilizer, plowing, harvesting, transportation) of each crop separately. The authors predict that one of the biggest threats to the future of the food system is the significant decrease in agricultural land due to urbanization and land pressure. They emphasized that this situation directly reduces the production capacity of the food system and negatively affects "self-sufficiency" rates, leading to increased imports as local production decreases, jeopardizing food security, and increasing external dependence.

Figure 4 illustrates the multilayered linkages and interactions of the food-production system, with inputs such as water, fertilizers, and energy, together with land and climate components (González-Rosell Barriga 2023).

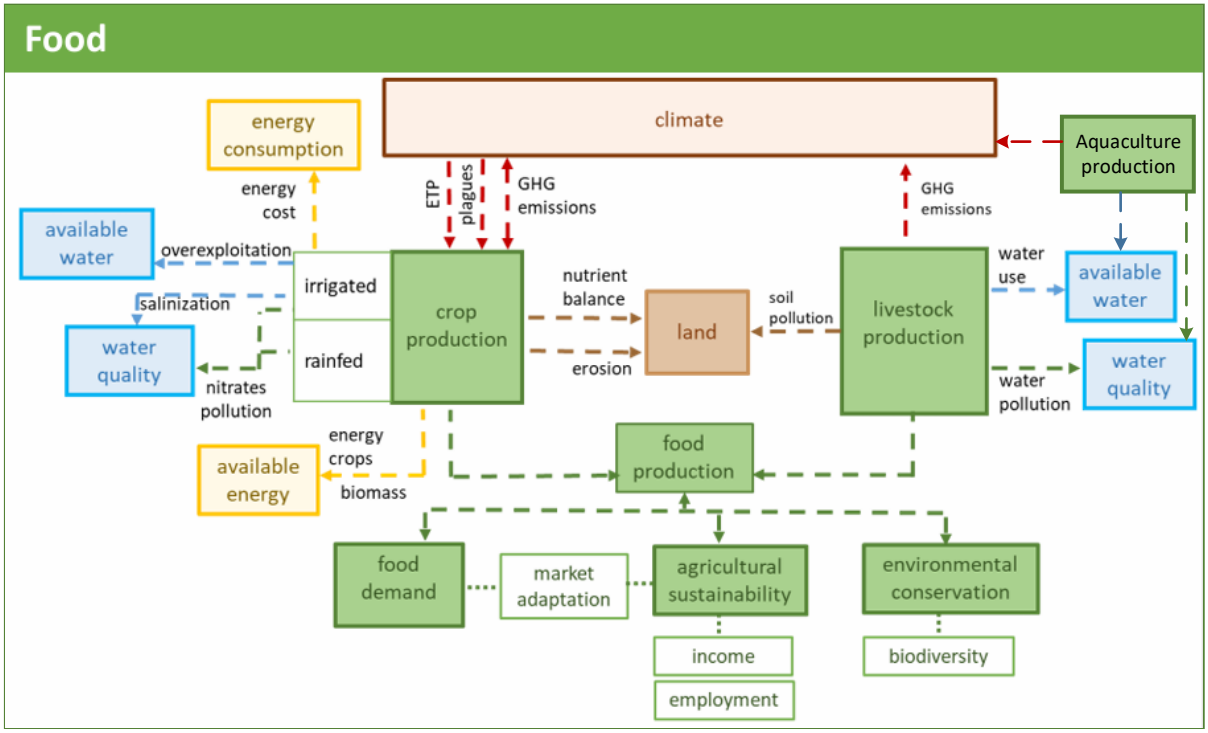


Figure 4- Food systems and components in WEF Nexus, modified from González-Rosell Barriga (2023)

In the diagram**,** food production is defined as the joint output of crop, livestock, and aquatic production processes. Crop production is directly linked to water availability and quality; irrigation-driven overuse and salinization lower groundwater levels, while nitrate pollution adversely affects aquatic ecosystems. At the same time, energy consumption raises agricultural production costs, strengthening the energy–food linkage. Livestock production exerts environmental pressure through intensive water use and waste-induced water pollution, and both modes of production contribute to climate change via greenhouse-gas emissions. The climate system influences production efficiency through evapotranspiration, pest outbreaks, and temperature shifts, while soil nutrient balance, erosion, and pollution processes degrade land quality. In the lower panel of the diagram, interactions among food demand, market adaptation, agricultural sustainability, environmental protection, and socioeconomic outcomes (income, employment, biodiversity) are emphasized. Thus, it is shown that water–energy–land–climate interactions shape not only production processes but also social welfare and environmental balance.

Across the value chain, food loss and waste occur at every stage, including production, transport, storage, processing, retail, and consumption. According to FAO's Global Food Losses and Food Waste report, roughly one-third of all food produced for human consumption is lost or wasted globally (FAO 2011). FAO (2019) estimates that about 14% of global food is lost between harvest and retail, while the UNEP (2024) finds that in 2022 approximately 1052 million tonnes of food were wasted at the retail, food service, and household levels, representing about 19% of food available to consumers. This equates to 132 kilograms per capita per year, of which 79 kg are wasted in households, 36 kg in food service, and 17 kg at retail (UNEP 2024). WWF (2021) suggests that if on-farm losses and unharvested produce are included, total food lost or wasted globally could reach as much as 2.5 billion

tonnes annually. Meanwhile, greenhouse-gas emissions attributable to food systems are estimated at 13.6 Gt CO_2-eq (Poore & Nemecek 2018; Ritchie et al. 2019).

3. Nexus Models and Tools

Understanding interactions among water, energy, and food is crucial for resource security, environmental and ecosystem protection, addressing cross-sectoral challenges, and developing actionable policies. The core objective is to maximize cross-sectoral synergies and minimize trade-offs so that resource use in one domain does not jeopardize the sustainability of the others. To support effective management and evaluation metrics, several modeling and analysis tools, representing diverse conceptual and computational approaches to modeling and assessing linkages among the water, energy, and food sectors, have been developed. Key examples include:

- MuSIASEM (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism)-a comprehensive diagnostic and simulation framework designed to evaluate the complex interactions within the WEF nexus at both national and subnational scales (Giampietro et al., 2013; Taghdisian et al., 2022).
- CLEWs (Climate–Land–Energy–Water Systems)- an optimization and scenario-based model focusing on assessing nexus interlinkages and integrating energy, land-use, and hydrological systems for national-level SDG planning (Howells et al. 2013; Ramos et al. 2021; Alexander et al. 2025).
- WEF Nexus Assessment 1.0 (Water-Energy-Food Nexus Rapid Appraisal Tool)- a framework, which allows for the evaluation of nexus strategies, policy measures, or interventions regarding bio-economic pressures. The set of policy scenarios includes electrical irrigation, bioenergy, and water desalination, among other interventions from the nexus perspective (Flammini et al. 2014).
- PRIMA (Platform for Regional Integrated Modelling and Analysis)- a system modelling tool that allows simulating the interactions between water, soil, energy, human socioeconomic systems, and natural systems. The modelling framework integrates various sectoral models and enables decision-making at the national and regional level (Kraucunas et al. 2015).
- The WEF Nexus Tool 2.0 serves as a multi-stakeholder platform for assessing resource allocation strategies, specifically designed to detect existing and emerging bottlenecks within nexus interconnections to mitigate resource stress (Daher & Mohtar, 2015; Daher & Mohtar, 2018). Degirmencioglu et al. (2019) evaluated the sustainability of the agricultural production system in Türkiye, focusing on the Gediz Basin, using the WEF axis approach. The methodological backbone of the study is the WEF Nexus Tool 2.0, which is used to analyze trade-offs between resources.
- Pardee RAND WEF Security Index operates as a web-based interactive framework that evaluates nexus security through the unweighted geometric mean of three sectoral sub-indices. These sub-indices incorporate multiple indicators to gauge both the availability and accessibility of resources (Willis et al., 2016; Mondal et al., 2023).
- Foreseer- Tool is a set of physical models for energy, water and land or any other custom analysis, such as climate change, or technological change. It allows tracking and visualizing the influence of future demand scenarios on energy, water, and land resource requirements (Allwood et al. 2016; Shinde 2017).
- NexSym- a modular platform, enhances existing nexus tools by employing explicit dynamic modeling to capture local techno-ecological interactions within WEF systems. It integrates ecosystem models with water, energy, and food production and consumption components, enabling users to construct, simulate, and analyze a localized system "flowsheet." (Martinez-Hernandez et al. 2017).
- Q-Nexus serves as a comprehensive assessment framework designed to quantify, simulate, and optimize the Water-Energy-Food (WEF) nexus as an interconnected resource system. This model facilitates the evaluation of various planning scenarios and policy alternatives by considering dynamic factors such as demand fluctuations, technological advancements, and resource allocation strategies (Karnib 2017; Karnib & Alameh 2020).
- WEAP–LEAP-The combination of WEAP (Water Evaluation and Planning) and LEAP (Long-range Energy Alternatives Planning) provides a connected modeling framework for the integrated analysis of water and energy systems. Individually, WEAP serves as a comprehensive tool for water resource planning, while LEAP offers a versatile platform for modeling energy systems and climate mitigation strategies (Liu et al. 2021; SEI 2019).
- WEFSIM is designed as a computational simulation framework to evaluate the dynamics of supply, consumption, availability, and reliability across water, energy, and food sectors. Operating on a nationwide scale, the model explicitly accounts for the complex interdependencies inherent in these resources (Wicaksono et al. 2020).
- WEF Nexus Index- a web-based tool that shows a comparative map by country, a composite index that integrates indices of the different sectors of the nexus considering the "access" and "availability" of each resource (Simpson et al. 2020; Simpson et al. 2022).
- GoNEXUS SEF: A guideline-driven framework for solution evaluation that employs systemic approaches to blend qualitative and quantitative methodologies. Its primary objective is to execute nexus-coherence assessments that strengthen the governance of the water-energy-food-ecosystems nexus (Gonzalez-Rosell et al. 2023).

These tools vary by spatial scale (local to global), modeling paradigm (indicator-, simulation-, optimization-based, or hybrid), and data intensity. Among them, the WEF Nexus Index stands out for its simplicity, transparency, and cross-country comparability, making it particularly valuable for macro-level policy benchmarking and SDG-focused resource assessment.

According to Cansino-Loeza et al. (2022), the WEF Nexus Index can serve as a metric for evaluating progress in a region's water, energy, and food security.

4. Methods and Dataset

The WEF Nexus Index is a quantitative assessment criterion used to measure countries' WEF security levels. As shown in Figure 5, the index is designed around access and availability subindices under three equally weighted sub-indices: the Water Index, the Energy Index, and the Food Index. Developed by Simpson et al. (2020), the WEF Nexus Index provides a transparent, quantitative tool for assessing national-level WEF security using a standardized set of indicators. Its formulation draws on a comprehensive statistical audit of 60 global indices, including the Environmental Performance Index, the Multidimensional Poverty Assessment Tool, the Global Competitiveness Index, and the Corruption Perceptions Index. Additional data sources include national statistical offices and international organizations such as the World Bank, the International Energy Agency (IEA), the Food and Agriculture Organization of the United Nations (FAO), the UN International Fund for Agricultural Development (IFAD), and the World Health Organization (WHO). Initially, 87 indicators were selected and then screened for global representativeness, reliability, and data availability.

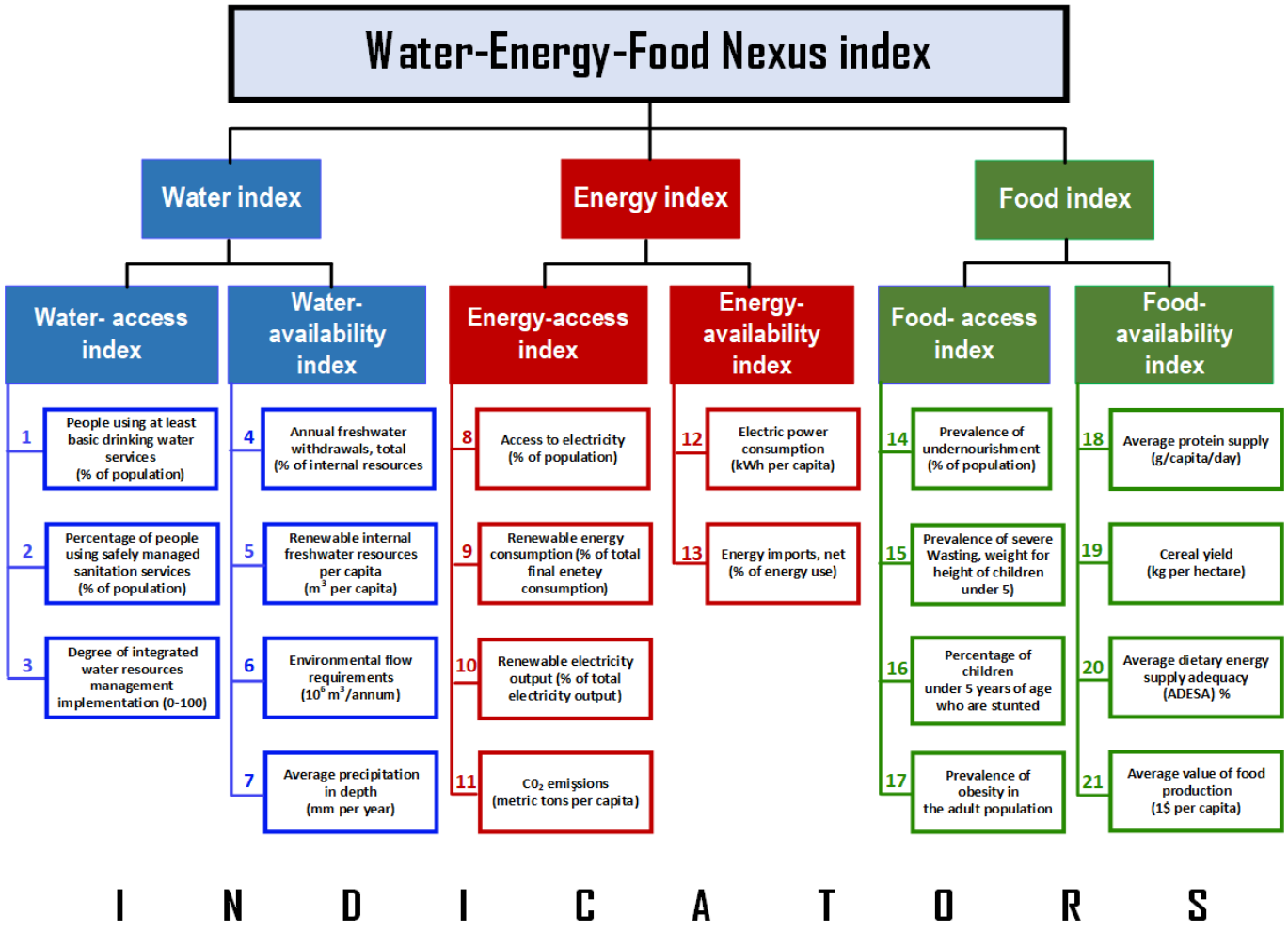


Figure 5- WEF Nexus Index, Water index, Energy index, Food index, access and availability indices (modified taking from Simpson et al. 2020)

As shown in Figure 5, the WEF model aggregates 21 indicators representing availability, access, and demand conditions in water, energy, and food systems: seven for water security, six for energy security, and eight for food security. The WEF Nexus Index, including subindices given in the following, is thus a composite indicator that combines 21 parameters:

1. The Water Index is determined by indicators such as access to safely managed drinking water, the degree of integrated water resources management, environmental flow requirements, and average annual precipitation.
2. The Energy Index covers indicators including access to electricity, the share of renewables, electricity generation, dependence on energy imports, and CO_2 emissions.
3. The Food Index is represented by indicators such as protein supply, rates of obesity and undernourishment, cereal yield, and the value of food production per capita.

This multidimensional approach seeks not only to capture the status of individual resources but also to measure the interactive integrity of water, energy, and food systems. Accordingly, the WEF Nexus Index provides a comprehensive analytical framework, aligned with the Sustainable Development Goals (especially SDG 2, SDG 6, and SDG 7), for comparing countries' resource-management performance, identifying weaknesses, and delivering evidence-based decision support for policymakers. Under the analytical design of the WEF Nexus Index, three equally weighted sub-indices are combined. Treating water, energy, and food on an equal basis, the framework defines access and availability levels for each sub-index. The Access Index represents the equitable distribution and accessibility of WEF resources, whereas the Availability Index concerns the physical presence and supply of those resources. As shown in Figure 5, indicators numbered 1 through 21 specify the measures of access and availability for each WEF resource. The weight assignments that capture interactions among the three resources in the WEF Nexus Index are provided in Table 1.

Table 1- Contributions of indicators, weight values of indices

Indicators (j)		***Sector indices***		*w(j)*	***Sub-indices***	
1	⅓	Water - access	⅙	1/18	Water	⅓
2	⅓			1/18		
3	⅓			1/18		
4	¼	Water - availability	⅙	1/24		
5	¼			1/24		
6	¼			1/24		
7	¼			1/24		
8	½	Energy - access	⅙	1/12	Energy	⅓
9	⅙			1/36		
10	⅙			1/36		
11	⅙			1/36		
12	½	Energy - availability	⅙	1/12		
13	½			1/12		
14	⅓	Food - access	⅙	1/18	Food	⅓
15	⅙			1/36		
16	⅙			1/36		
17	⅓			1/18		
18	¼	Food - availability	⅙	1/24		
19	¼			1/24		
20	¼			1/24		
21	¼			1/24		

The WEF Nexus Index thus enables a holistic, policy-oriented assessment of resource security that reflects both the efficiency of resource use and the degree of societal access. The index has been applied at multiple scales, national (Simpson et al. 2020) and local (Ingram et al. 2021). At the global scale, countries' performances can be compared via interactive visualization tools on the web platform *wefnexusindex.org*. Beyond simple benchmarking, the WEF Nexus Index serves as an analytical bridge between resource security and policy integration, helping translate the WEF Nexus paradigm from theory into practice.

The WEF Nexus model relies on normalization equations (1 – 4) defined by Ingram et al. (2021) to ensure cross-country comparability. For country i, the WEF Nexus Index (WNI) can be calculated as the arithmetic mean of the Water Index (WI), the Energy Index (EI), and the Food Index (FI):

$$WNI_i = \frac{WI+EI+FI}{3} \tag{1}$$

Each sectoral sub-index (SI), for the Water (WI), Energy (EI), and Food (FI) pillars, is computed as a weighted arithmetic mean of the normalized indicator values, aggregated under the Access and Availability sub-indices:

$$\begin{Bmatrix} WI_i \\ EI_i \\ FI_i \end{Bmatrix} = \frac{SI_{Access,i}+SI_{Availability,i}}{2} \tag{2}$$

In the sub-indices, w_j are taken into account for according to the assigned weight and the indicator's normalized value:

$$SI_i = \sum_{j=1}^{n} w_j x_{ij}^{norm} \tag{3}$$

For j-indicator that determines the globally observed value (obs) of i-country, the normalized score on a 0–100 scale using the min–max method is computed as:

$$x_{ij}^{norm} = \frac{x_{ij}^{obs} - x_j^{min}}{x_j^{max} - x_j^{min}} \times 100 \quad (4)$$

The Mendeley datasets used within the scope of the WEF Nexus Index are listed in Table 2.

Table 2- The WEF index Mendeley datasets

Version	*Published*	*Dataset Description*	*Reference*
V1	Sep. 10, 2020	21 indicators for 170 nations,	Simpson 2020a
V2	Oct. 6, 2020	21 indicators of 170 nations,	Simpson 2020b
V3	Mar. 10, 2022	21 indicators for 181 countries	Simpson 2022
V4	Sep. 26, 2023	21 indicators for 181 countries	Simpson 2023

Using these datasets and the web platform *wefnexusindex.org*, the 21 raw indicator values for Türkiye, covering water, energy, and food, were extracted for the period 2019–2023 (Table 3).

Table 3- Raw indicators of Türkiye for WEF Nexus Index

	Indicators	*2019*[1]	*2020*[2]	*2021*[3]	*2022*[4]	*2023*[5]
	Water access					
01	The percentage of people using at least basic drinking water services (%)	98.9	98.9	97	97	97
02	The percentage of people using at least basic sanitation services (%)	96.4	97.3	99.2	78.4	78.4
03	Degree of IWRM implementation (1-100)	69.5	69.5	72	78	72
	Water availability					
04	Annual freshwater withdrawals, total (% of internal resources)	18.5	27.8	26.4	26.4	27.1
05	Renewable internal freshwater resources per capita (m^3)	2947	2811	2798	2757	2698
06	Environmental flow requirements (10^9 m^3 per year)	77	77	77	77	77
07	Average precipitation in depth (mm per year)	593	593	593	593	593
	Energy access					
08	Access to electricity (% of population)	100	100	100	100	100
09	Renewable energy consumption (% of total final energy consumption)	13.4	13.4	11.9	14.1	13.7
10	Renewable electricity output (% of total electricity output)	32	32	32	32	32
11	CO_2 emissions (metric tons per capita)	4.5	4.7	5	4.8	4.8
	Energy availability					
12	Electric power consumption (kWh per capita)	2847	2847	2847	2847	2815
13	Energy imports, net (% of energy use)	75.2	75.2	75.2	75.2	75.2
	Foody access					
14	Prevalence of undernourishment (%)	1.2	2.5	2.5	2.5	2.5
15	Percentage of children under five years of age affected by wasting (%)	1.7	1.7	1.7	1.7	1.7
16	Percentage of children under five years of age who are stunted (%)	9.5	6	n/a	n/a	5.5
17	Prevalence of obesity in the adult population (18 years and older)	32.2	32.1	32.1	32.1	32.1
	Food availability					
18	Average protein supply (g per capita per day).	120	101.7	109.3	110.3	110.9
19	Cereal yield (kg per hectare).	3105	3257	3164	3164	2919
20	Average Dietary Energy Supply Adequacy (ADESA) (%)	158	149	156	157	159
21	The average value of food production (I$ per capita)	484	483	159	159	159

[1]: Simpson 2020a, [2]: Simpson 2020b, [3]: Simpson 2022, [4]: Simpson 2023, [5]: wefnexusindex.org

The global dataset updated via the web platform covers 184 countries. In this study, to ensure consistent cross-country evaluation at the global scale were considered. Türkiye's position was assessed both worldwide, among 160 countries, and within the OECD, among 35 member countries.

5. Results and Discussion

Because water resources, energy, and food production are inextricably linked, actions taken in one sector often affect the others negatively, at different levels and scales. By addressing the three systems holistically, and assuming effective governance, the WEF Nexus recognizes that a change in one implies a significant change in the other two, focusing on ensuring water, energy, and food security. In this study, Türkiye's water and energy resources, food production, climate conditions, and greenhouse gas emissions are first examined in depth using up-to-date data sources. The WEF Nexus Index and its outputs for 2019–2023 are then evaluated comparatively at both global and OECD scales.

5.1. WEF resources

5.1.1. Water

Within Türkiye's borders, there are surface-water resources organized across 25 river basins, together with a total of 320 natural lakes of various sizes, some of which dry up during the summer months. The Euphrates–Tigris River basin is the country's largest, accounting for 30.5% of total water potential (Figure 6).

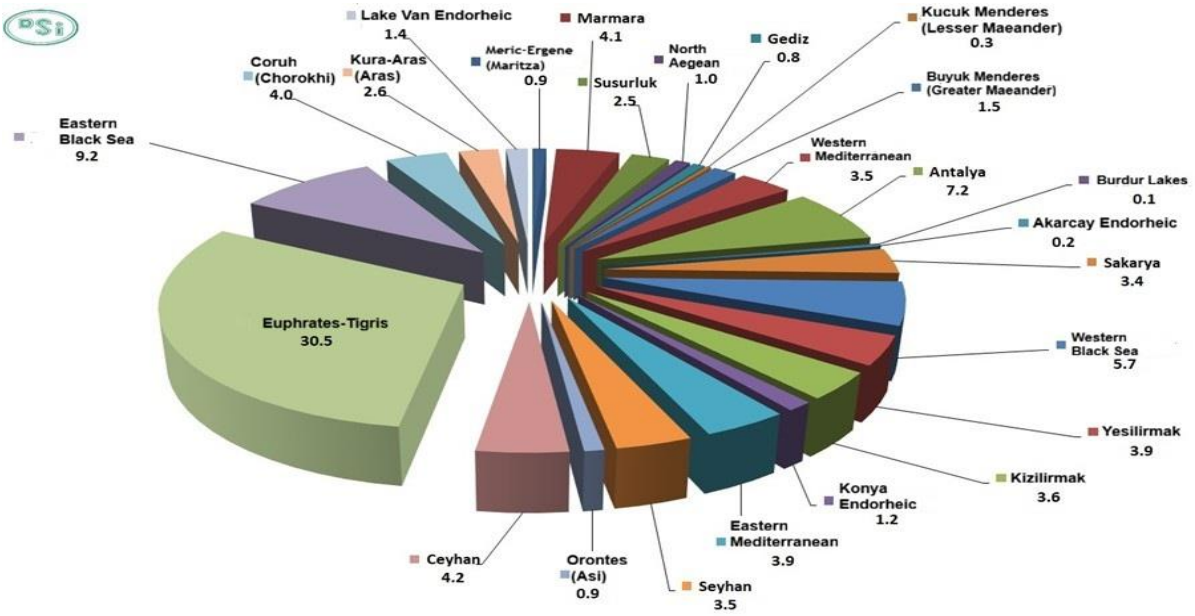


Figure 6- Annual average surface water potential rates by basin (DSİ 2025)

According to the FAO AQUASTAT database, the long-term average precipitation is 593 mm; total precipitation amounts to 465.7 billion m^3 total internal renewable water resources (IRWR) are 227 billion m^3, surface-water capacity generated internally by river basins is 186 billion m^3 and the technically and economically exploitable water-resources potential totals about 112 billion m^3 (FAO AQUASTAT 2025). For irrigation, hydropower, and domestic water supply, 1017 dams, serving a gross irrigated area of 4.7 million ha and providing 3.6 billion m^3 of annual drinking-water capacity, are in active use. The installed capacity of the 750 dams operated by public and private entities is 32288 MW, producing on average 110.9 TWh of electricity per year (DSİ 2025).

Türkiye's variables covering environment and health, geography and population, irrigation and drainage development, water resources, and water use are summarized in Table 4 (FAO AQUASTAT 2025).

Table 4- Türkiye's water statistics for 2022 (FAO AQUASTAT 2025)

Long-term average annual precipitation in depth (mm per year)	593
Long-term average annual precipitation in volume (10^9 m^3 per year)	465.7
Surface water produced internally (10^9 m^3 per year)	186
Total internal renewable water resources (IRWR) (10^9 m^3 per year)	227
Total renewable water resources (10^9 m^3 per year)	211.6
Total exploitable surface water potential (10^9 m^3 per year)	98
Regular exploitable groundwater potential (10^9 m^3 per year)	14
Total exploitable water potential (10^9 m^3 per year)	112
Total renewable surface water (10^9 m^3 per year)	171.8
Total external water (10^9 m^3 per year)	7
Environmental Flow Requirements (10^9 m^3 per year)	76.97
Water Stress (%) (SDG 6.4.2.)	47.89
Total renewable water m^3 per capita[1]	2475
Total exploitable water m^3 per capita[1]	1310
Population (2024) (10^6)	85.5
Agricultural water withdrawal (10^9 m^3 per year)[2]	56.13
Industrial water withdrawal (10^9 m^3 per year)[2]	1.3
Municipal water withdrawal (10^9 m^3 per year)[2]	7.14

[1]: Calculated according to population,[2]: Not consistent with DSI records.

According to AQUASTAT, of the 64.6 billion m^3 total withdrawals, 56 billion m^3 are agricultural, 7 billion m^3 municipal, and 1.3 billion m^3 industrial, figures that are inconsistent with the DSI database. In DSI's 2023 records, for 574 mm of precipitation the average annual surface-water potential by basin is 178.7 billion m^3; nationwide, 57 billion m^3 of water are withdrawn, of which 44 billion m^3 (77%) for irrigation and 13 billion m^3 (23%) for domestic (12%) and industrial (11%) uses. The total amount of surface water used in irrigation is 33.8 billion m^3; the total groundwater allocation for irrigation is 12.3 billion m^3; and the groundwater allocation for drinking, household, and industrial water is 6 billion m^3 (DSİ 2025). Although Türkiye's renewable water capacity per capita is 2475 m^3, its exploitable (available) water capacity per capita is 1310 m^3, placing the country at the threshold of Falkenmark water scarcity (500–1,000 m^3 per capita).

5.1.2. Energy

Türkiye's primary energy consumption in 2023 and 2024 was 1961 TWh and 2093 TWh, respectively; of this total, 31.6% was oil, 24.5% natural gas, and 24.0% coal, amounting to 80% from fossil fuels, and 20% from renewable energy sources (Energy Institute 2025). For 2024, annual per-capita energy consumption is approximately 24 MWh. In addition, total final energy consumption (TFEC) and its sectoral shares are provided in Table 5. Of the 1344.7 TWh consumed in total, 28.4% is used in industry, 28.2% in transport, 21.6% in households, 12.4% in commercial and public services, 4.71% in agriculture–forestry–fisheries, and 4.8% in non-energy uses (IEA 2025 a; IEA 2025 b).

Table 5- Distribution and rates of total final energy consumption (TFEC) in Türkiye by sector in 2023 (IEA 2025)

Sectors	*TFEC (TWh)*	*%*
Industry	381. 5	28.4
Transport	378.8	28.2
Residential	290.0	21.6
Commercial and Public Services	166.7	12.4
Agriculture / Forestry	62.1	4.6
Fishing	1.5	0.1
Non-energy use	64.2	4.8
Total	1344.7	100

According to data from the Turkish Electricity Transmission Corporation (TEİAŞ), Türkiye's installed capacity reached 119991 MW in July 2025, comprising 39% fossil fuels, 26.9% hydropower, and 34% renewables (including waste heat). The proportional distribution by source is shown in Figure 7. The installed capacity of renewables, including hydropower, rose to 72898 MW.

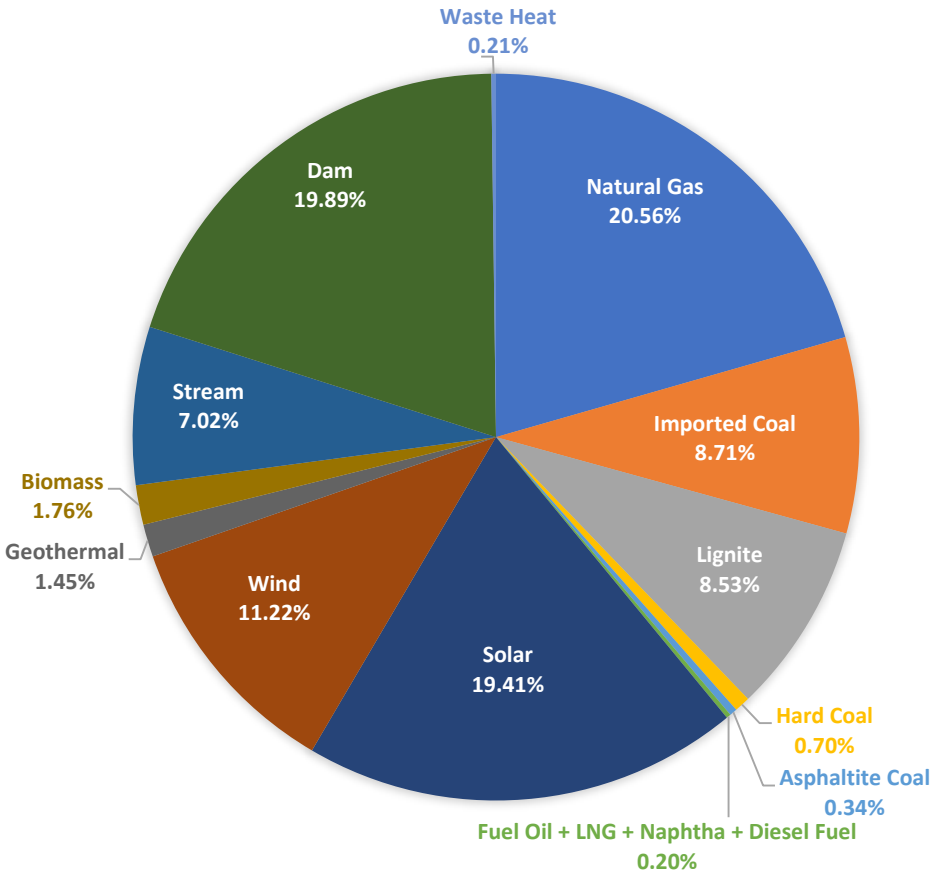


Figure 7- Türkiye's installed electrical energy capacity at the end of July 2025 (TEİAŞ 2025)

Türkiye's electricity generation and consumption in 2024 were 348.9 TWh and 347.9 TWh, respectively. Of total generation, 35.2% was from coal, 18.9% from natural gas, 21.5% from hydropower, 10.5% from wind, 7.5% from solar, 3.2% from geothermal, and 3.2% from other sources. In July 2025, total electricity generation amounted to 34.8 TWh (TEİAŞ 2025).

5.1.3. Food

In Türkiye, total food production in 2024 amounted to 168 million tonnes, comprising 137.7 million tonnes of crop production and 30.2 million tonnes from fisheries and aquaculture as well as livestock production (including dairy products). The proportional breakdown is presented in Figure 8.

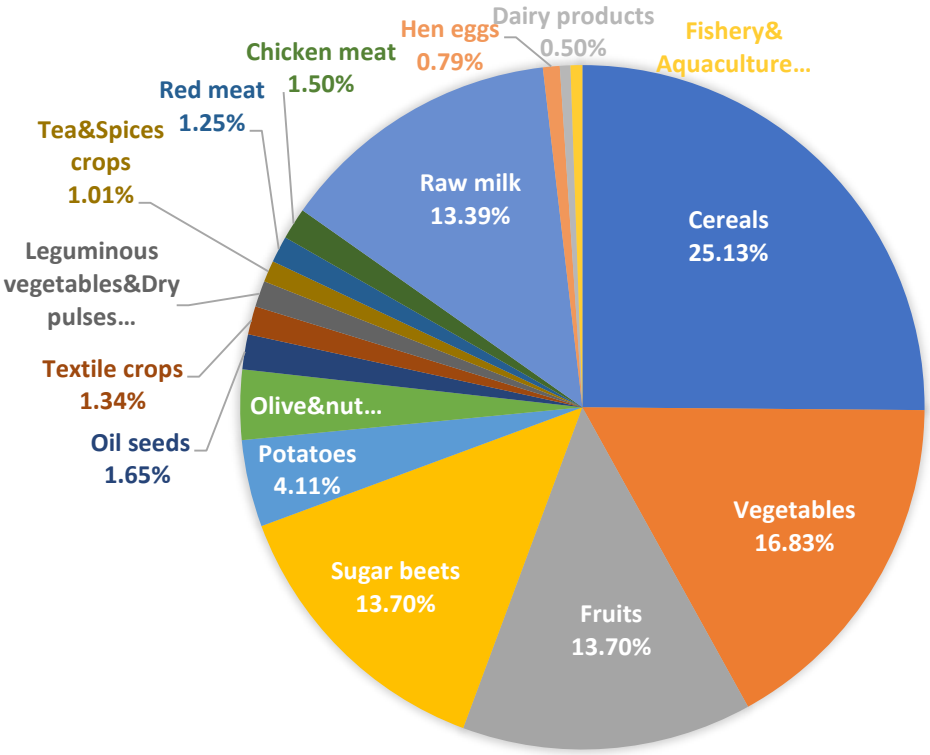


Figure 8- Türkiye's food production in 2024 (TUIK 2025)

As crop products, cereals totaled 42.2 million tonnes, vegetables 28.3 million tonnes, fruits, and sugar beet 23.0 million tonnes, potatoes 6.9 million tonnes, and olives plus tree nuts 5.6 million tonnes. As animal products, red meat amounted to 2.1 million tonnes, poultry meat 2.5 million tonnes, and raw milk 22.5 million tonnes; hen eggs totaled 1.33 million tonnes (21.1 billion eggs). Dairy products amounted to 834,425 tonnes, and fisheries & aquaculture to 933,194 tonnes. In Türkiye, a total of 38.64 million hectares of agricultural land were used in 2024; yields for cereals, oilseeds, pulses, and raw materials used in textile ranged between 50 and 1000 kg per decare (Figure 9; TÜİK 2025, FAOSTAT 2025; OECD/FAO 2024).

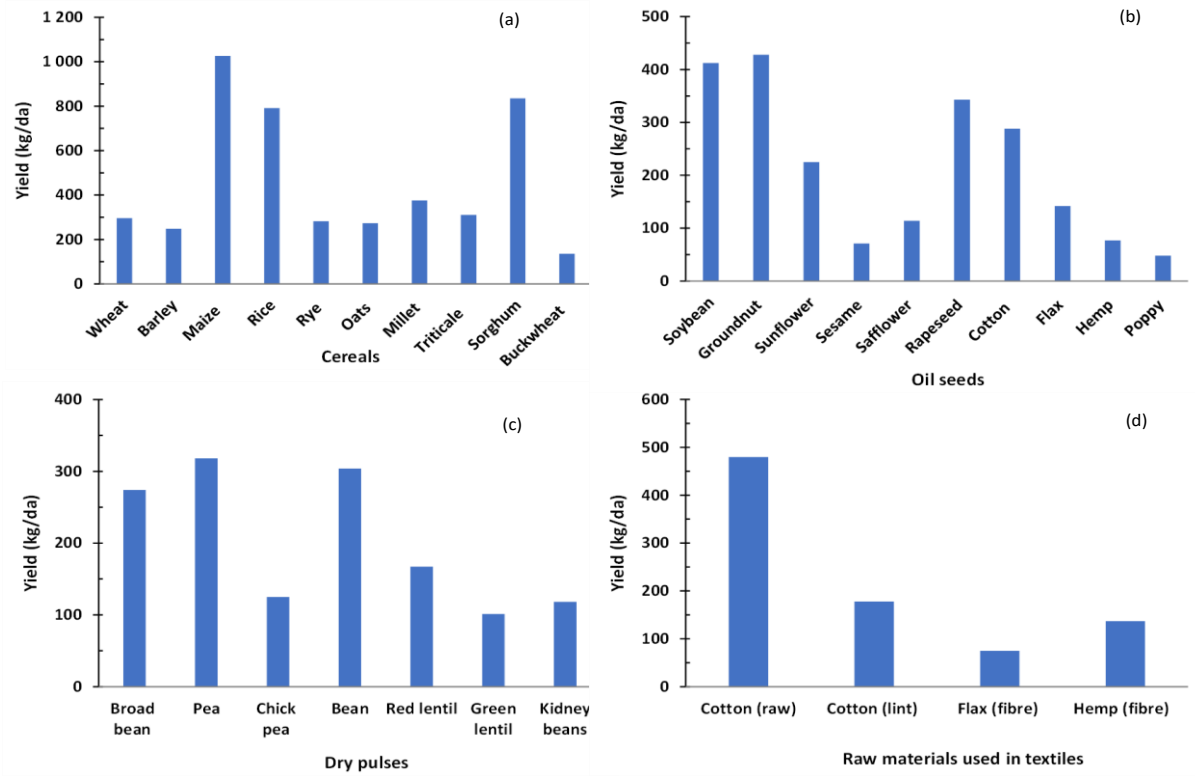


Figure 9- The yields in kg per decare of (a) cereals, (b) oilseeds, (c) pulses and (d) raw materials products used in textiles

5.2. Climate

Based on 30-year normal for temperature and water-year precipitation from 220 homogenously distributed stations of the Turkish State Meteorological Service (1991–2020), temperature change and cumulative precipitation were evaluated for 2023, 2024, and 2025 (through September). Türkiye's mean temperature in 2023 was 15.1 °C, which is 1.2 °C above the 1991–2020 average of 13.9 °C. In 2024, the national mean temperature was 15.6 °C, i.e., 1.7 °C above the 1991–2020 normal of 13.9 °C. In 2025, the mean temperatures for January, March, May, June, July, August, and September were warmer than their respective normal by 2.6 °C, 3.0 °C, 0.9 °C, 1.2 °C, 1.9 °C, 1.4 °C, and 0.8 °C, respectively (MGM 2025a; see Figure 10).

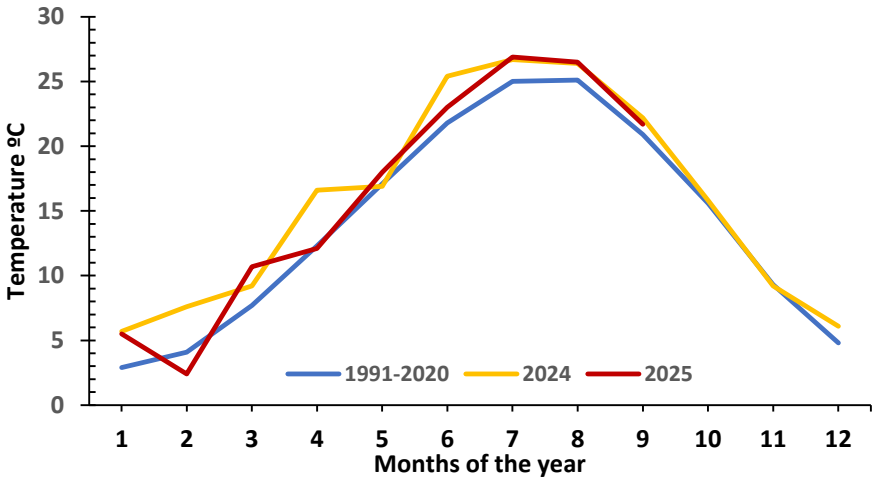


Figure 10- Comparison of Türkiye's average temperatures against 1991-2020 averages (MGM 2025 a)

Figure 11 presents the monthly area-averaged cumulative precipitation normal for Türkiye's water year (1 October–30 September), together with the trajectories for 2023, 2024, and 2025. Precipitation in the 2025 water year (1 October 2024–30 September 2025) remained below both the long-term normal and last year's totals.

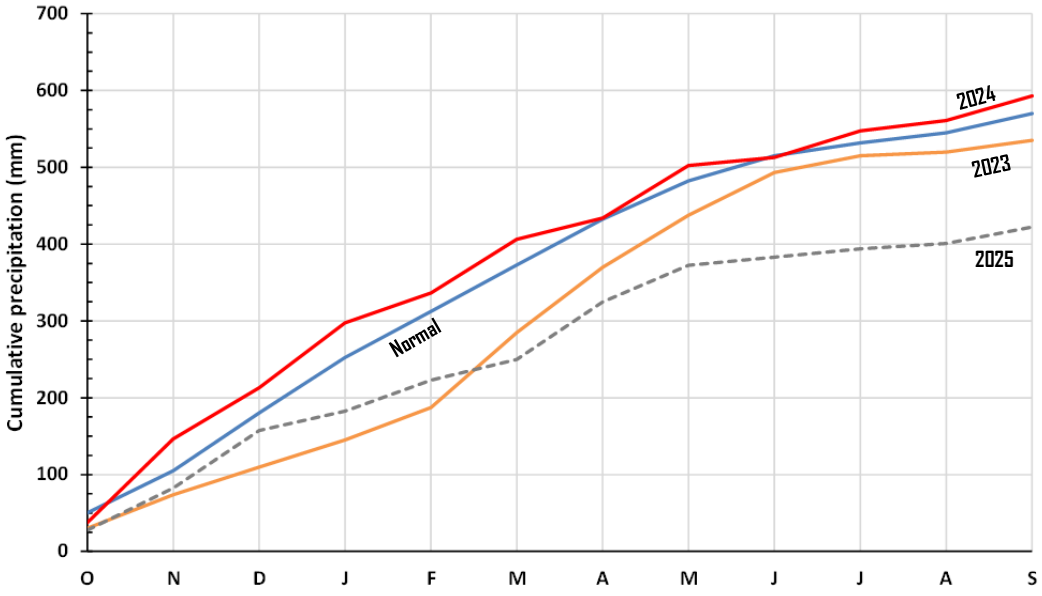


Figure 11- Comparison of Türkiye's areal-averaged cumulative precipitation (MGM 2025 b)

The precipitation normal map is shown in Figure 11(a), the 2025 precipitation anomaly map in Figure 12(b), and the SPI drought map in Figure 12(c). Based on these graphs and maps, pronounced declines in Türkiye's precipitation regime are evident in both 2023 and 2025. The average precipitation recorded in the 2025 water year was 422.5 mm.

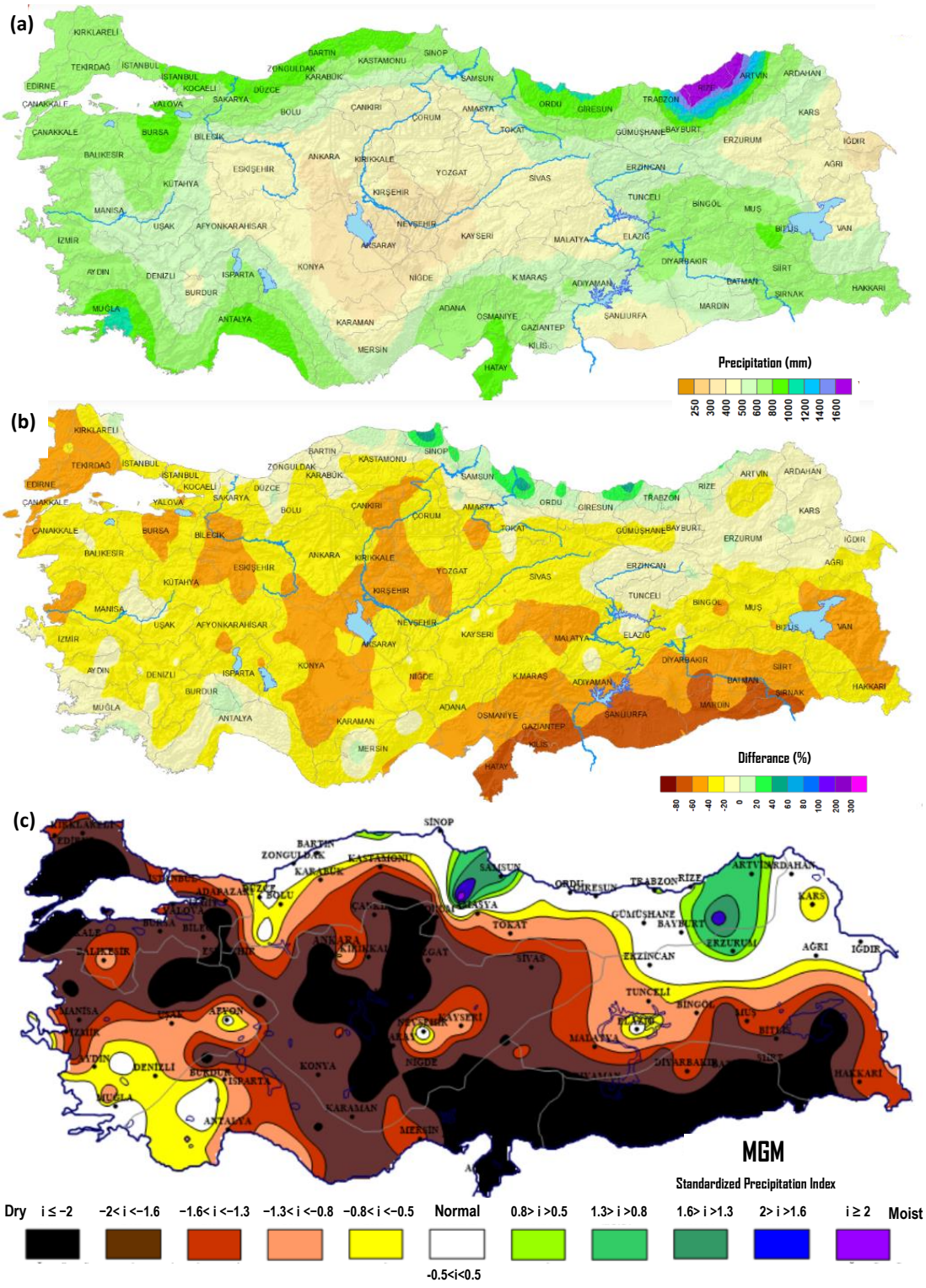


Figure 12- Comparison of water year precipitation with normal, (a) Map of areal-averaged cumulative normal precipitation for the water year (1 Oct. – 30 Sep) between 1991-2020, (b) 2025 difference map with normal (c) Meteorological drought map based on Standardized Precipitation Index (October 2024-September 2025) (MGM 2025)

The water-year normal is 573.4 mm (1991–2020), and precipitation for the 2024 water year was 597.0 mm. Türkiye's nationwide water-year precipitation has fallen to the lowest level of the past 52 years, coming in 26% below the normal and 29% below last year's total. In parts of the southern Southeastern Anatolia Region and around Hatay, declines locally exceeded 60%, whereas around Sinop, Samsun, Ordu, Giresun, and Trabzon, increases of over 20% were observed. At the province scale, the highest total precipitation was recorded in Rize with 1812.1 mm; the largest increase relative to normal occurred in Giresun (+30%). The lowest total precipitation was observed in Şanlıurfa with 182.8 mm, and the greatest decrease relative to normal occurred in Hatay (–66%) (MGM 2025b).

5.3. Greenhouse gas emissions

The sectoral distribution of greenhouse gas (GHG) emissions is critical for identifying priority areas in countries' climate-change mitigation strategies. As of 2024, Türkiye's total GHG inventory has been assessed to include emissions from energy, industry, agriculture, waste, and process-related sources. In this framework, the climate impact of each gas (CO_2, CH_4, N_2O, and F-gases) is calculated using the 100-year Global Warming Potential (GWP-100) factors defined in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). By expressing the impacts of different gases in a common unit, carbon-dioxide equivalent (CO_2eq), this method enables cross-sector comparisons.

According to IPCC AR5 GWP-100 values, Türkiye's total GHG emissions in 2024, covering CO_2 (fossil only), CH_4, N_2O, and F-gases, amounted to 579.5 Mt CO_2eq, composed of 79.4% CO_2, 13.6% CH_4, 5.5% N_2O, and 1.5% F-gases. Annual per-capita emissions were 6.76 t CO_2eq. Agriculture accounted for 67.9 Mt CO_2eq (11.7% of total GHGs), with an internal gas split of 3.1% CO_2, 68.3% CH_4, and 28.6% N_2O (Table 6; Crippa et al. 2025; EDGAR 2025).

Table 6- Türkiye's total greenhouse gas emissions in 2024, Mt CO_2eq (according to GWP-100 AR5)

Sectors	*CO_2*	*CH_4*	*N_2O*	*F-gases*	*Total*	*%*
Agriculture	2.1	46.4	19.4	-	67.9	11.7
Buildings	72.7	1.2	1.2	-	75.0	12.9
Fuel Exploitation	15.6	9.6	0.0	-	25.3	4.3
Industrial Combustion	75.0	0.1	0.2	-	75.3	13.0
Power Industry	140.9	0.1	2.6	-	143.7	24.8
Processes	54.4	0.0	6.3	8.9	69.6	12.0
Transportation	99.3	0.3	0.6	-	100.2	17.3
Waste	0.0	20.8	1.7	-	22.5	3.9
Total	460.0	78.6	32.0	8.9	579.5	
%	79.4	13.6	5.5	1.5	100	

5.4. WEF Nexus Index

Using datasets covering 2019–2023, Türkiye's national WEF Nexus scores, indicating its global WEF Nexus levels, were compared at the World and OECD scales. Türkiye's WEF Nexus index values for these five years are displayed in the radar chart in Figure 13.

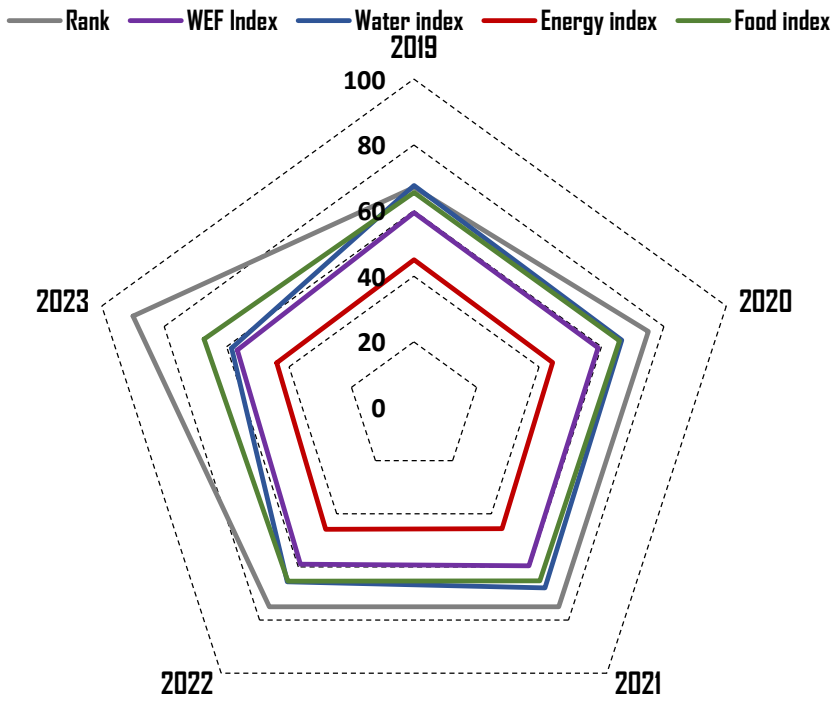


Figure 13- WEF Nexus index, rank, Water, Energy and Food indices

While Türkiye stayed at moderate levels at a ranking of 67 among 170 countries, with a WEF Nexus index of 59.4 in 2019, Türkiye ranked 90th globally with an average score of 56.6 out of 100 in the 2023 WEF Nexus Index. This score was derived from sub-indices of 65.7 for water, 45.8 for energy, and 67.3 for food.

The five-year WEF access and availability indicators are shown in the radar chart in Figure 14. Although the Water Access index is around 80.1, the Water Availability index remains at 36.8 with a decline of roughly 8-12 points in 2023.

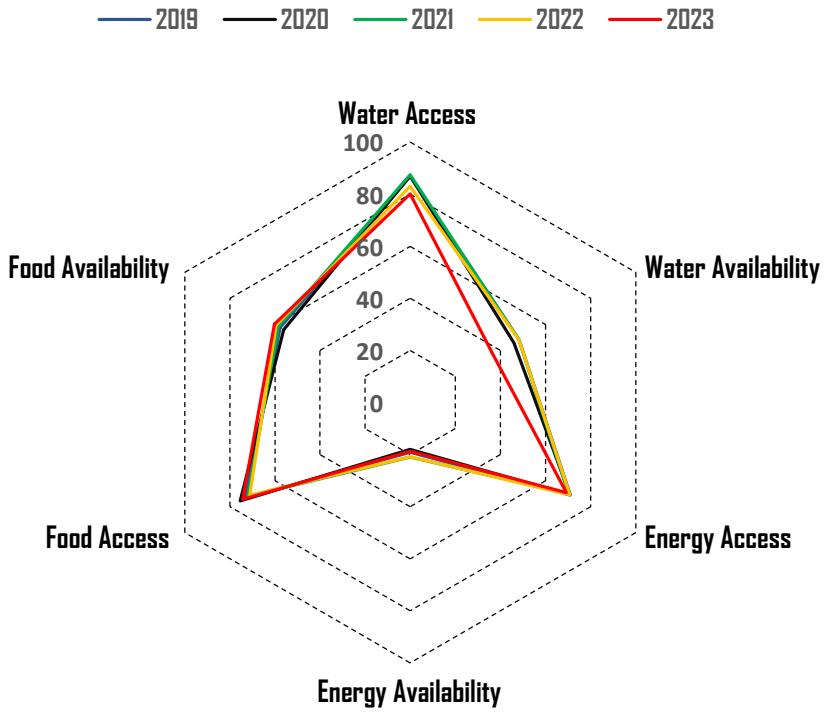


Figure 14-Access and availability indicators of Türkiye for water, energy, and food

The water index represents a moderate performance in Türkiye's WEF balance. Water index indicators show that Water Access remained high throughout 2019–2023 in the 80-87.5 range, whereas Water Availability was lower in the 36.8-48.2 range. This indicates notable progress in access to drinking water and sanitation services despite limited renewable capacity on the physical supply side. The findings suggest that, despite advances in water infrastructure, climatic drought, groundwater abstraction, and water-quality challenges constrain supply. This brings to the fore the balancing problem between urban water management and agricultural water use. As Hristova et al. (2024) note, similar structural imbalances are observed in Eastern European countries, heightening sensitivity to long-term climate impacts. In Türkiye's case, this vulnerability is especially pronounced in agricultural areas where water use relies on energy-intensive pumping systems.

The Energy Index, averaging 45 points, is the weakest component of Türkiye's WEF Index and the main factor depressing the overall Nexus score. During 2019–2023, the energy pillar remained largely stagnant, with no marked upward trend. At the sub-indicator level, Energy Access is high (69-71), whereas Energy Availability is low (18-21). This configuration indicates that, despite a high electrification rate, energy-supply security is weak. The conceptual model of 'energy-centered fragility' proposed by Smith Lopez et al. (2024) helps explain this outcome: high dependence on energy imports, the limited share of renewables, and energy-price volatility generate both economic and environmental security risks. The continued dominance of fossil fuels, particularly natural gas and coal, in Türkiye's energy mix is the principal reason for the pillar's low value. This situation increases costs across the water and food systems, making energy expenditures a decisive factor in agricultural production and water supply.

The Food Index, averaging 65.8 points, is Türkiye's strongest domain within the WEF Nexus. Between 2019 and 2023, it exhibited a relatively steady upward trend. In particular, the rise in Food Availability (71–75.5) reflects improvements in agricultural production capacity, food supply, and dietary diversity. Türkiye's robust agricultural infrastructure and broad production potential are the principal factors underpinning the food pillar. By contrast, Food Access (56–60) has remained comparatively constrained, a pattern linked to regional income disparities, rural poverty, and volatility in food prices. As El Majdoubi & El Ayadi (2024) note in the Moroccan context, even countries with strong production capacity may see deterioration in food-access indicators due to social inequalities. In Türkiye, narrowing this gap requires not only production-oriented policies but also social policies explicitly targeting access to adequate nutrition.

The 2019–2023 radar charts show that Türkiye's WEF structure is strong on access indicators but limited on availability indicators, what the literature terms a 'high-access–low-supply' (Simpson et al. 2023). This pattern is pronounced in the water and energy systems: while service access is high, resource supply remains under environmental pressure. Overall, Türkiye's WEF Nexus Index profile is grounded more in interdependence than in balance. As the energy pillar remains weak while the food system retains resilience, overall resource security exhibits a fragile configuration. This clearly indicates that Türkiye must strengthen integration across WEF systems on its path toward sustainable development.

Indicators for 2023 were evaluated across the world (160 countries) and the OECD (35 countries). The radar chart in Figure 15 was constructed using WEF Nexus index scores for Iceland, ranked 1st, and Türkiye, ranked 90th, in addition to the world and OECD averages. Türkiye's 2023 WEF Index score (56.6) trails Iceland by 24.5 points, the OECD average by 12.3 points, and the world average by 0.9 points.

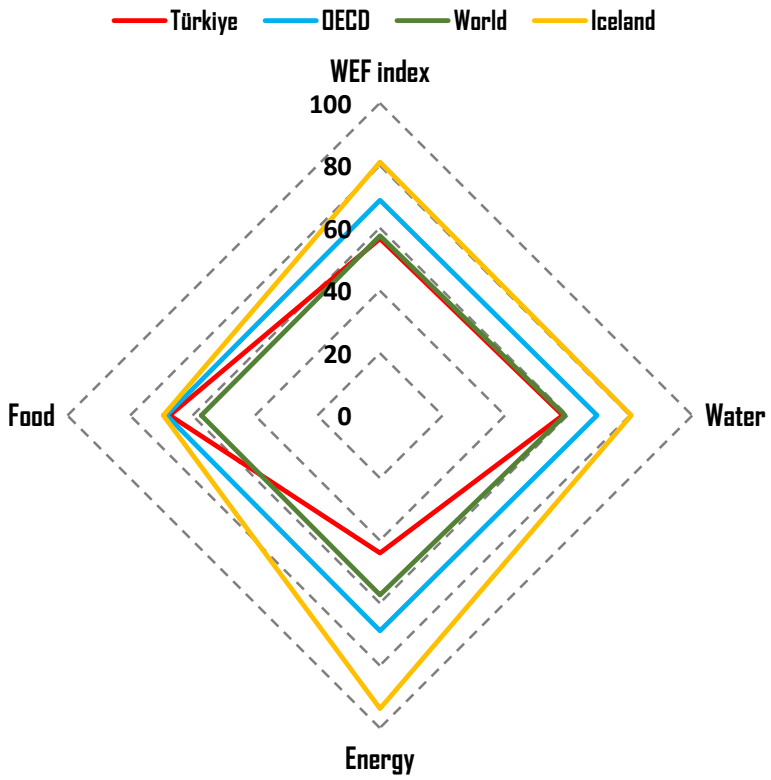


Figure 15- Comparison of WEF Nexus indices for Türkiye, Iceland, OECD, and the World (2023)

By sub-index, Türkiye's Water Index (58.5) is lower by 21.9, 10.95, and 0.7 points relative to Iceland, the OECD average, and the world average, respectively; its Energy Index (44) is lower by 48.9, 24.9, and 13.4 points, respectively. Although Türkiye's Food Index (67.3) is 2 points below Iceland and 1 point below the OECD average, it exceeds the world average by 10 points.

The bar chart in Figure 16 displays the WEF Nexus scores for Iceland, which are the highest indices, alongside the OECD and world averages, to facilitate the overall comparison.

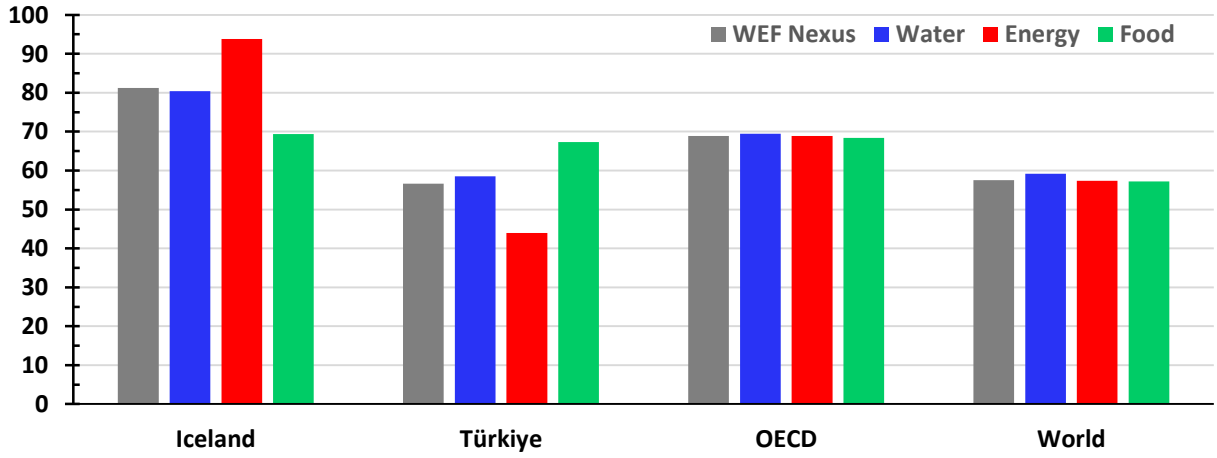


Figure 16- Comparison of the WEF Nexus Index between Iceland, Türkiye, OECD, and World averages

While most OECD countries cluster in the 65–85 range, Türkiye's 2023 scores, Water Index 58.5, Energy Index 44, and Food Index 67.3 for overall WEF Index 56.6, remain comparatively low. Among the three core sectors, food is relatively strong, water is moderate, and energy is weak, revealing an imbalance across primary resources. This profile indicates that Türkiye's WEF balance is fragile around the energy pillar, yet comparatively resilient in terms of food security. Overall, the trajectory of the indices suggests progress on the access dimension of resources, with limited improvement on availability.

Additionally, the rankings of WEF indices across the 35 OECD countries are shown in Figure 17. Iceland leads the WEF Nexus Index (81.2), Canada leads the Water Index (81), Iceland leads the Energy Index (93.8), and Ireland leads the Food Index (83.5). It is notable that Türkiye ranks near the bottom across all indices and, despite positive effects on the food side, places 26th.

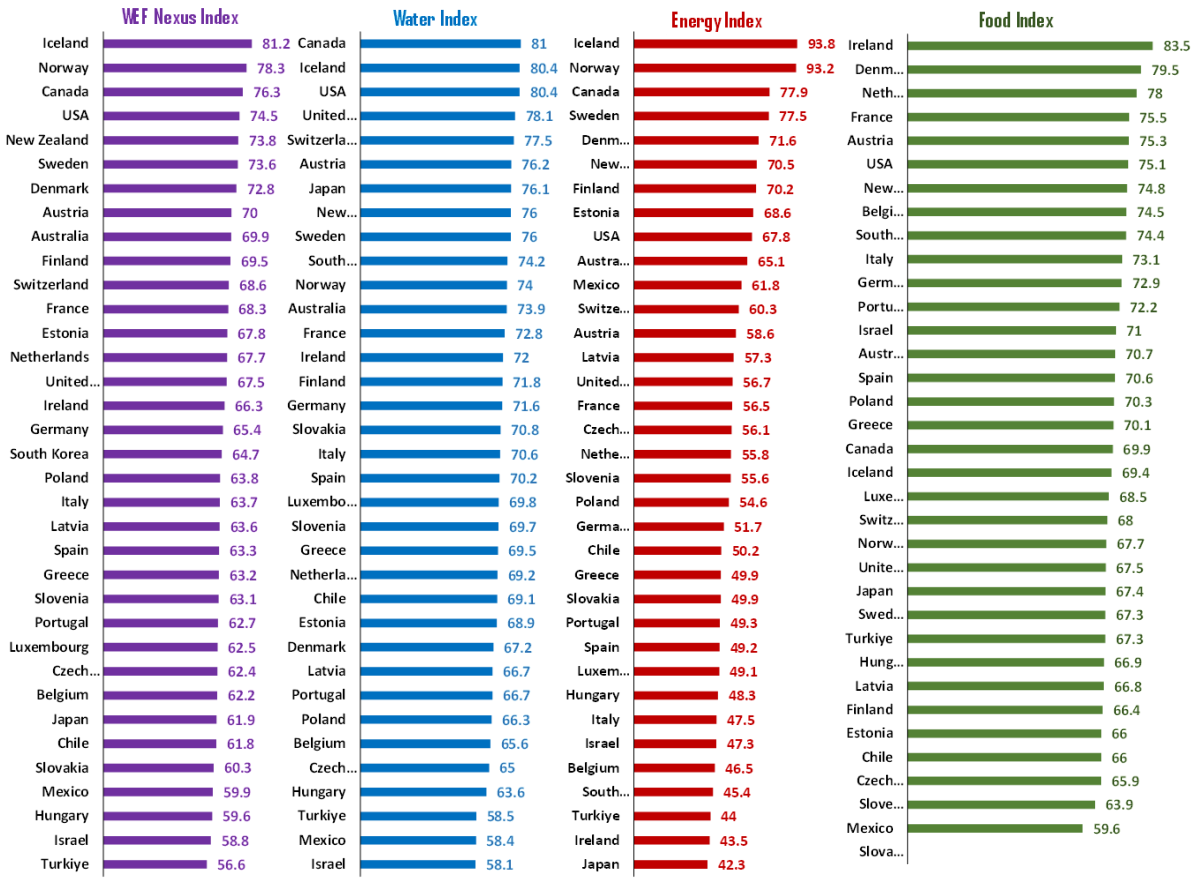


Figure 17- WEF Nexus indexes and country rankings for 35 OECD countries (2023)

Compared with OECD peers, Türkiye lags in resource efficiency, renewable-energy deployment, and institutional coordination. Türkiye's WEF Nexus configuration appears partially integrated yet unbalanced: while water and food systems exhibit high access capacity, the energy system is constraining in terms of both supply security and environmental sustainability. This weakness in the energy index spills over into the other two sectors, via electricity costs for irrigation and the use of fossil inputs in agricultural production, thereby shaping interdependencies within the Nexus.

Given Türkiye's population of 85.5 million, the renewable water potential per capita is 2475 m^3, yet the available water capacity per capita is 1310 m^3. With annual withdrawals of 57 billion m^3 (77% for agricultural irrigation) and a water-stress ratio of 47.9% (SDG 6.4.2), all sectors are at risk, underscoring the need to develop balanced WEF security policies.

Türkiye's per-capita energy consumption of 24 MWh/year, combined with 75% energy import dependence, means that despite recent growth in renewable capacity, levels remain low, weakening energy-supply security and keeping carbon intensity high, factors that depress Türkiye's WEF index. With 80% of primary energy based on fossil fuels, associated GHG emissions directly affect the WEF system: per-capita emissions taken as 4.5-5 t CO_2eq (Table 3) have risen to 6.76 t CO_2eq in 2024, heightening environmental vulnerability. The agricultural sector accounts for 11.7% of national GHG emissions, signaling the climate impact of the food system. Collectively, these data show that the fossil-heavy energy structure exerts pressure on both climate and water–energy–related sustainability.

From a food-systems perspective, Türkiye has a strong production capacity close to the OECD average, with 168 million tonnes of total food output in 2024. Of this, 25% is cereals, 17% vegetables, 14% fruits, 13% sugar beet, and 13% dairy products. These figures buoy the food indicators: a broad product mix and robust agricultural capacity lift access to food (average 73.3). However, rural–urban income gaps and price volatility weigh on food availability (average 58.4).

Globally, if one considers that food production accounts for about 26% of total GHG emissions, that one-third to two-fifths of food produced is discarded before consumption, and that roughly 10% of water is lost, it becomes clear that the deep interconnections of the Nexus must be translated into concrete policies to secure sustainable living standards.

Situated in the mid-latitudes between the Equator and the Arctic, Türkiye experiences variable precipitation under the influence of continental and maritime polar air masses (cP, mP) in winter and continental and maritime tropical air masses (cT, mT) in summer. However, due to climate change, global warming, demographic shifts, rising living standards, increasing water demand, and inadequate water management, a transition from a water-rich to a water-scarce country is an imminent risk. Climate data show that during 2023–2025, Türkiye's national mean temperature rose by 1.2–1.7 °C above the long-term average, and that in the 2025 water year the average precipitation of 422.5 mm was 26% below normal. Such climatic variability, by inducing fluctuations particularly in water availability, may further destabilize the WEF balance and trigger severe disruptions across all climate-sensitive sectors.

By making sectoral performance comparable on a common scale, the WEF Nexus Index reveals where strengths and weaknesses cluster. In Türkiye's case, the imbalance '*food > water > energy'* produces multifaceted sectoral effects and spillovers that pull down the level of sustainable development. Taken together, Türkiye's water, energy, and food resource potential alongside climate and GHG emissions, these quantitative findings indicate that policies and strategies informed by WEF Nexus scores must be developed.

Simpson et al. (2022) emphasize that the WEF Index serves as a "starting point" for integrated resource-planning and security debates; in particular, the access dimensions align with socio-economic inequalities, while the availability dimensions reflect biophysical supply conditions. Hoff (2011) and Kurian (2017) stress that an effective WEF Nexus governance framework should integrate three complementary dimensions:

- *Coherent policies*- Align agricultural, water, and energy policies across ministries and administrative scales through institutional coordination.
- *Resource efficiency and circularity*- Deploy technologies that optimize water and energy use per unit of food produced (e.g., renewable-powered irrigation, wastewater reuse, precision agriculture).
- *Resilience and adaptive capacity*- Enhance systems' ability to respond to climatic, economic, and demographic shocks.

Building on Simpson et al. (2022) and Smith Lopez et al. (2024), regional applications show that the WEF Index provides a practical framework for cross-sector coordination, investment prioritization, and monitoring–evaluation:

- Energy: Raising renewable electricity output and the share of renewables in TFEC, improving energy efficiency and loss-reduction, and lowering import dependence can lift the energy index and generate leverage on the overall score.
- Water–energy–food simultaneity: Irrigation modernization and energy-efficient agricultural water management (pressurized irrigation, pump efficiency, PV–grid hybrid solutions) yield co-benefits for both water use and energy efficiency.
- Access dimensions: Social policies targeting equitable access to drinking water, sanitation, electricity, and healthy food can simultaneously support the water–energy–food sectors.

To overcome urgent challenges, hunger, energy scarcity, water scarcity, improved health services, and the shift to a sustainable economy, securing the availability of these resources is vital (Shannak et al. 2018; David & Adepoju 2021). As Rhouma et al. (2025) and Simpson et al. (2023) highlight, adopting the WEFE-Water-Energy-Food-Ecosystems framework will both safeguard the water cycle and reduce the carbon footprint across energy–food production chains. As stated in the study by Değirmencioğlu et al. (2019), water conservation (drip irrigation) or the transition to renewable energy alone is not sufficient to maintain sustainability in the Gediz Basin. The Sustainability Index proves that land management, crop pattern selection (drought-resistant species), and technological investments should be addressed with a holistic Nexus approach.

5.5. Limitations

While this study provides a comprehensive indicator-based evaluation of Türkiye's WEF Nexus profile, several limitations inherent to composite indicators and data availability must be acknowledged. First, condensing the complex interactions of the WEF nexus into a set of national-level indicators involves a degree of simplification. As noted by Simpson et al. (2022), summarizing a nation's integrated resource management status is inherently complex, and indicator-based assessments serve primarily as an entry point for identifying macro-level trends rather than providing detailed, site-specific solutions. Consequently, while this study effectively profiles Türkiye's national performance, it may mask regional disparities (e.g., between the water-rich Black Sea region and the arid Central Anatolia) that would require basin-level analysis. Second, the study relies on secondary data from national and international open-access databases. Variations in data reference years across different indicators and potential gaps in time-series data may influence the precision of the nexus profile. Furthermore, consistent with global nexus assessments, this study primarily focuses on biophysical and economic indicators. Due to the lack of quantifiable data linked directly to nexus sub-pillars, complex socio-political drivers, and the full extent of cross-border resource trade-such as virtual water flows and detailed energy import dependencies-could not be fully integrated into the index structure. Finally, the assessment assumes equal weighting for the primary pillars (water, energy, and food) to reflect a balanced nexus approach. However, in practice, policy priorities in Türkiye may favor specific sectors depending on immediate national security or economic goals, which implies that future studies could benefit from sensitivity analyses involving different weighting scenarios to test policy robustness.

6. Conclusions

Considering sectoral securities within the WEF Nexus, resources must be safeguarded and co-managed effectively, with respect to availability, accessibility, stability, and productivity. Ensuring water security is closely tied to delivering food and energy security, protecting ecosystems, and reducing key vulnerabilities and risks associated with climate change. When water and energy consumed during food production, and the resulting emissions, are assessed together, the economic, environmental, and social costs of food loss and waste are exceedingly high.

A nation without adequate food, and without solutions, faces decline and, ultimately, extinction. A nation deprived of a stable energy supply is like a fruitless tree; it cannot complete its development, nor can its national income rise. For a nation suffering water scarcity, sovereignty and future prosperity are imperilled.

6.1. Critical evaluations

The analysis of Türkiye's WEF Nexus Index reveals a distinct dichotomy between resource "access" and "availability," highlighting specific strengths and critical vulnerabilities that require targeted policy interventions.

1. Weakest Point: Energy Security and Availability

The Energy Index is the lowest score of 44.0 in 2023, with an alarming Availability sub-score of 19.5. The primary driver of this weakness is Türkiye's heavy reliance on energy imports (75.2% dependency) and fossil fuels, which creates vulnerability to global market fluctuations and increases the carbon footprint. Although renewable energy consumption accounts for around 13-14%, it is still insufficient to offset the dependency deficit. The immediate priority must be accelerating the energy transition.

Policies should focus on the following:

(i) Incentivizing "agrivoltaics" to generate energy on agricultural land without compromising crop yield,

(ii) Expanding wind and solar capacity to reduce import dependency,

(iii) Utilizing agricultural biomass waste for bioenergy production to create a circular energy system.

2. Strongest Point: Food security and access

The Food Index is the strongest score of 67.3, indicating robust performance in providing food security. Türkiye benefits from a strong agricultural production base and high accessibility to food resources. The "Food Access" sub-indicators are generally high, reflecting the country's capacity to feed its population. However, this strength is threatened by the water-energy dependency of the food sector, climate change, and drought. High water withdrawals for agriculture (approx. 77% of total use) put pressure on the nexus balance. To sustain this strength, the focus must shift from "production maximization" to "resource-efficient production." Promoting drought-resistant crop varieties and modernizing irrigation infrastructure are essential steps to decouple food security from water stress.

3. Critical Threshold: Water availability

While water access is a high score of 58.5, the availability score of 45.5 signals growing physical stress, as well as disruption of the rainfall regime and drought. The moderate index score masks the underlying threat of climate change and inefficient water management in a semi-arid geography. The "availability" score is negatively impacted by high withdrawal rates relative to renewable internal freshwater resources. Implementation of strict Demand Side Management (DSM) policies is required. This includes enforcing Integrated Water Resources Management (IWRM) principles more rigorously, currently scored of 77%, and investing in irrigation technologies and wastewater recycling technologies for industrial and agricultural reuse to relieve pressure on freshwater reserves.

6.2. Strategical solutions

For Türkiye, strategic solutions within the WEF Nexus, organized by the three sectors, include:

1. Water Index: Integrated basin management; reducing non-revenue water/losses; VPD-sensitive irrigation scheduling; digital irrigation solutions.

2. Energy Index: Grid investments that raise the share and flexibility of renewables; improved quality of rural electrification; electrification of agricultural production; efficiency gains and loss reduction (e.g., cold chain).

3. Food Index: Targeted programs that improve economic access to healthy foods and nutrition quality metrics; productivity in agricultural production; nutrition policies for vulnerable groups.

While the water and food components constitute the strong axis of the WEF system, the energy pillar is the key constraint on overall balance. This structure reflects a "high access–low availability" imbalance and underscores the importance of WEF adaptation policies anchored in the country's energy transition.

In sum, the future of Türkiye's WEF Nexus policies should rest on three core axes:

- Energy transition and carbon reduction- Increase the share of renewables; diversify energy-supply security.
- Water–energy integration- Raise energy efficiency in irrigation and food-processing systems.
- Strengthened institutional coordination- Govern agricultural, energy, and environmental policies holistically.

Author Declarations

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