Water–Energy–Food Nexus

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The availability of water, energy and food plays a key role in meeting the basic needs of the world population and allowing them to achieve prosperity and supports the UN's sustainable development goals (SDGs). These three fundamental resources are closely interrelated, with their deep interdependencies reflected in various concepts of the **'water**–**energy**–**food nexus'** (W–E–F).

Keywords: nexus W–E–F ; nexus FW–FL–FS ; food waste ; food losses

1. Introduction

The resources of water and energy are becoming increasingly sensitive. Water scarcity has been identified as a pervasive threat to global society and economy with an estimated two-thirds of the global population already experiencing its severe effects [1]. The depletion of fossil energy resources and the rising demand for energy coupled with the high environmental costs of energy production make energy issues similarly dire. Additionally, societies in many countries are experiencing food shortages for various reasons such as overpopulation, drought or poverty, causing hunger and malnutrition. Political, economic and natural crises (e.g., droughts, floods, hurricanes) as well as the changing climate and growing population aggravate this situation even further. At the same time, however, huge amounts of food are wasted in all countries and at various stages of the food chain, straining the sensitive water and energy resources. It is estimated that, globally, one-third of the total food production results in food waste (FW) and food losses (FL) [2]. This has prompted various mitigation policies at regional, state and international levels, such as the objective to reduce 50% of food loss and waste at the retail and consumer levels by 2030, along with an unspecified reduction at earlier supply chain stages, set by the UN sustainable development goals (target 12.3.) [3].

Food wastage can be categorized as food waste (FW) and food loss (FL), where FW is defined as inedible food and FL as food appropriate for human consumption that is discarded or left to spoil, regardless of the cause [4]. The waste and loss of food occur at all stages of the food supply chain, including during transportation, from agricultural food production, harvesting, storage and food processing into products to wholesale, retail, restaurant and institutional food service and household use. While systematic data on FWL and its environmental impact at each stage of the food supply chain are not available, it is estimated that, worldwide, 413 MT of food is wasted at the agricultural production stage, 293 MT in postharvest handling and storage, 148 MT in processing, 161 MT in distribution and 280 MT in consumption [5]. For comparison, in the EU, 39% of all food loss is estimated to occur in food manufacturing [6]. Another important category to consider in the context of FWL is food security (FS), which refers to the confidence in the food production system, supply chain management, availability, continuity and sufficiency for the consumer and industry now and in the future [7]. Together with FW and FL, food security builds a FW–FL–FS nexus.

Food waste and loss in the early stages of the supply chain can be reduced by exchanging resource-intensive products for more sustainable foods. In developed countries, consumers have a wide range of food products to choose from, offered by the food industry. They prefer to buy products that are already partially prepared for consumption (convenience foods) rather than those that require lengthy pre-processing and often choose novelty over rational products [8]. A rich market with a constant supply of novelty and innovation opposes a traditional and saturated market that lacks freshness. Today, many consumers are fascinated by different eating habits and food products with new sensory and organoleptic characteristics. This is due to, among other things, the increasing mobility of societies and the acceleration of technological development. This results in changing values and the emergence of quite distinct generational differences every ten years or so. Successive generations, BB, X, Y (so-called millennials) and the current generation Z, differ in their approach to food and nutrition due to biophysical, cultural and social dimensions [9]. Some are looking for products which are easy to prepare, others for foods with new taste or nutritional value and still others for foods with enhanced health properties. Additionally, over the past 30 years or so, consumers have been becoming increasingly concerned with sustainability and climate change, which has given rise to green consumerism with preferences for ecological and/or sustainable products [10]. The food industry is, on the one hand, responding to these preferences by bringing desirable products to the market. On the other hand, it is actively seeking higher profits and market niches, e.g., by launching its own novel (cost and/or resource-efficient) offers.

2. Water–Energy–Food Nexus

More than 1 billion people nowadays are undernourished, another 1 billion have no safe water and 1.5 billion have no source of electricity [11]. People are also becoming increasingly aware from painful experiences that "(w)ater, energy and food are inextricably linked" [12]. Access to these resources and their effective management underpin development progress and are prominent in the UN sustainable development goals (SDGs), among other activities. Projections show that the world economy will need more electricity in 2030 compared to in 2007 [13]. At the same time, global water demand could rise by between 35% and 60% between 2000 and 2025 and double by 2050 [14]. In addition, to meet projected demand, cereal production will have to undergo a 50% increase, and meat production an 85% increase, between 2000 and 2030 [15]. The most important factor in choosing the right tool for addressing the resource nexus is the clear identification of the problem at hand, which interlinkages of resources are important, the data needed to assess their availability and in which part of the world the problem occurs.

On the other hand, however, the linkages between freshwater supply and energy production and the extraction and processing of minerals and energy have not been given due attention. Moreover, environmental challenges and economic fluctuations make these relationships even more uncertain and unpredictable, especially given the changing political dynamics of the international system, with the rise of powers such as China, India and Brazil. Understanding and quantifying these resource linkages can also present opportunities such as productivity gains, substitution, reuse and recycling and reduced consumption, to name a few, while minimizing the risks associated with resource management [16]. However, not all modeling tools have the capabilities to deal with all kinds of problems anywhere in the world [17].

Additionally, the approach taken and the decisions made in the policy-making process reflect the perspective of the policy maker, meaning that if a water perspective is taken, food and energy are the users of the resource, and, from a food perspective, energy and water are the inputs, etc. As noted by Lee and Ellinas, "anticipated bottlenecks and constraints in energy, water and other key natural resources and infrastructure bring new political and economic challenges, as well as new and difficult-to-manage instabilities" [18]. Making policies for one sector may temporarily improve performance in that sector of the economy, but this is highly unlikely to be sustainable over the long term. A holistic approach can lead to a more optimal allocation of resources, improved economic efficiency, reduced environmental and health impacts and improved conditions for economic development.

W–E–F Nexus Models

Due to the inextricable links between the systems of water, energy and food management and their external resources and biotic environment, the sustainability triangle in the W–E–F (water–energy–food) nexus is evolving to include more dimensions, creating larger models such as the water–energy–land–food [19], water–energy–climate–food [20] or ecosystems–water–food–energy [21] frameworks. This creates challenges for integrating and optimizing the components of this multi-centric nexus, as examined and evaluated by Leck et al. [22] and other scholars [18][19][20]. A 'simple' nexus relationship between water, energy and food is often represented as a triangle, with the respective resource subsystems connected by bidirectional lines or arrows to describe the bilateral interactions between them. The figure is also sometimes drawn as a circle depicting interactions with the natural, political and climatic environments.

This bidirectionality of interactions between the subsystems in the W–E–F nexus model can be described as follows: the relationship between W–E is defined as "availability and use of water for energy production" (green and blue water); the inverse relationship E–W as the "impact of energy production on water quantity and quality"; the relationship between F–W as the "impact on water quantity (changes in run-off) and quality (e.g., salination, eutrophication)"; the inverse relationship W–F as "availability and use of water for food production, (green and blue water)"; the relationship F–E as the "direct impact from food production to energy use and energy security"; and E–F is described as "the direct impact of energy production on food security including agriculture and fisheries" [23].

According to Albrecht et al. [24], "while the W-E-F nexus offers a promising conceptual approach, the use of W-E-F nexus methods to systematically evaluate water, energy, and food interlinkages or support development of socially and politically relevant policies has been limited". In the cited review, the authors showed that the survey methods were largely non-specific, with a high prevalence of qualitative methods limited to a small number of scientific disciplines, making inference difficult and diminishing usefulness for practice. After all, it is expected that a nexus should organize and explain the relationships that exist between resources and systems in a systematic way and through quantitative methods [25]. In another publication, the authors examined the influence of qualitative and quantitative factors related to the environment, health, economics and social relations that may be different in different geographic and political environments [26]. Their study concluded that the W–E–F nexus can be an effective vehicle for advancing water and sustainability issues and recommends further research and demonstration projects to test the extent to which the W–E–F framework could be helpful in increasing understanding and collaborative governance approaches.

In another publication [27], de Grenade et al. placed the W–E–F nexus between interacting social (human) and natural (physical) systems. Their review of recent literature indicated that publications generally include the natural environment, social-ecological systems and external conditions. In the above-mentioned paper, the authors wrote: "…The concepts of environment, land, ecosystems, ecosystem services, and climate change play a structural role in these discussions, however the context of how these concepts are integrated, at what scales, for whom, and to what end varies widely. Furthermore, within nexus scholarship, consideration of social-ecological systems theory, resilience, and adaptive capacity remain largely unexplored". Based on their research and analysis, they proposed to extend the notion of the nexus to the broader environment, as shown in **Figure 1**. Bleischwitz et al. [28] used a pentagonal model (**Figure 2**) to present the W–E–F nexus with two elements attributed to SDG targets: materials and land.

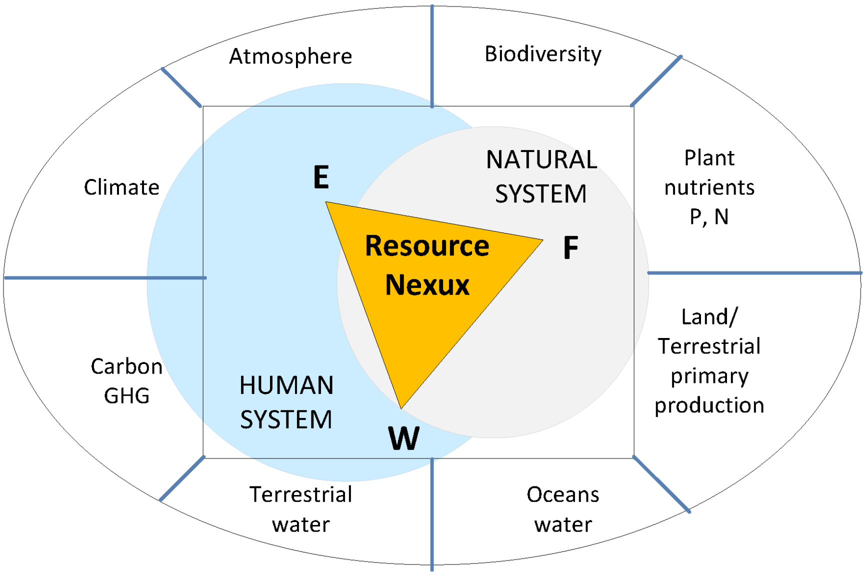

Figure 1. W–E–F nexus in environment. Source: own drawing inspired by de Grenade et al. [27].

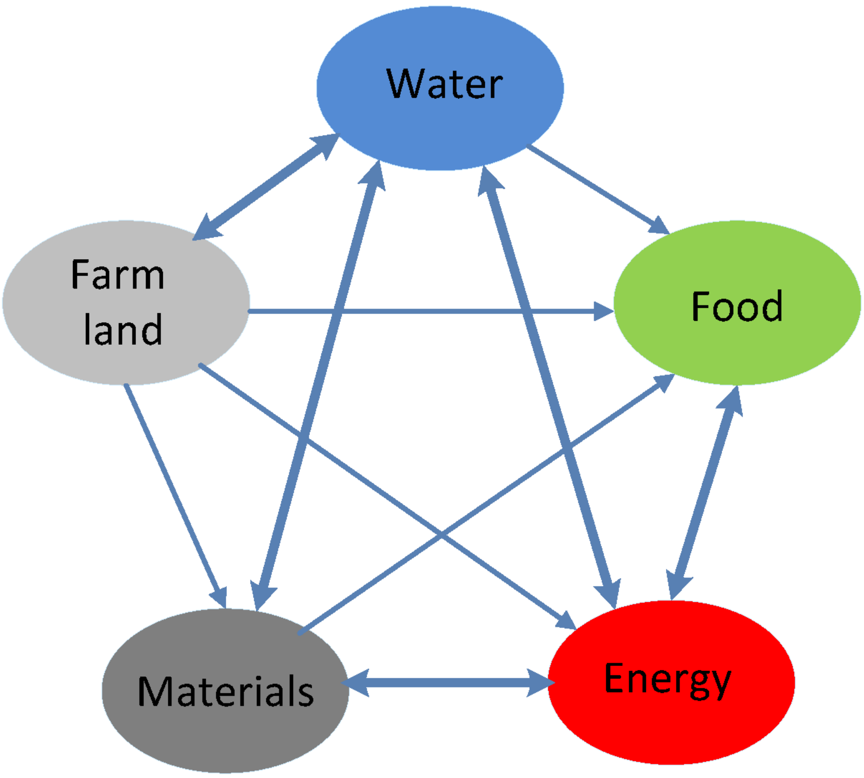

Figure 2. Five-element nexus: water, food and energy, with addition of farm land and materials. Thick arrows with two arrowheads indicate two-way interactions, and thin arrows indicate one-way interactions. SDG indicators have been omitted. Source: own depiction inspired by Bleischwitz et al. [28].

A very sophisticated and complex W–E–F model was proposed by Biggs et al. [29] to conceptualize environmental livelihood security as ‘‘… refer[ring] to the challenges of maintaining global food security and universal access to freshwater and energy to sustain livelihoods and promote inclusive economic growth, whilst sustaining key environmental systems functionality, particularly under variable climatic regimes…’’. This comprehensive model seeks to cover all types of water, energy and food resources on Earth and their interdependences. Biggs et al. presented a novel framework for incorporating livelihood dynamics into the W–E–F nexus which builds on its strength and livelihood approaches to explore and develop the concept of ‘environmental livelihood security’. The authors argued that an integrated and holistic approach to measuring and achieving sustainable development outcomes in multi-scale systems is able to better inform development policies and programs.

Other models in the literature seek to integrate physical, technical, social and economic components of the nexus in novel ways, e.g., in [30]. The introduction of the ‘ecosystem’ or ‘waste’ perspective in the middle of the W–E–F nexus points to the main sources of wastage: the complex production and consumption of food from field to table and water resources.

The methodology presented by Santeramo et al. [30] was used to develop a series of nexus assessments of selected river transboundary basins in Europe. The objective was to identify trade-offs and impacts across sectors and countries and to propose possible policy measures and technical actions at national and transboundary levels to reduce intersectoral tensions. This was carried out jointly with policy makers and local experts. Such a method offered the opportunity to better involve key economic sectors, in particular, the energy and agriculture sectors, in the dialogue over transboundary water resource uses, protection and management. Similar studies are being carried out in other parts of the world. One of their objectives is to improve water allocation policies, which can help to reduce negative climate change and its impact on water and energy availability for agriculture. This is expected to affect surface water levels and, subsequently, produce better yields and more energy from hydroelectricity [31][32].

An interesting approach to the proposal to extend the traditional W–E–F nexus to include waste was presented by Bowen et al. [33]. This construction can be seen as an isosceles triangle with waste placed in its center or as an equilateral tetrahedron with waste on top of the pyramid. The relationship between W, E and F is bilateral. For example, the food sector supports the production of biofuels and biogas. The energy sector supports transportation and production of fertilizer and the food chain. The introduction of waste and losses into the nexus is very important and creative because it indicates the main sources of their creation: food and water.

In another proposal [34], which is more general, the nexus is described as an analytical tool or method to quantify the links among the nexus nodes, including various characteristics or properties of food, energy and water. Some examples are shown in **Table 1**.

Table 1. Other possible synonyms of W–E–F nexus.

Food	Energy	Water
Security	**Security**	**Hardness**
Availability	**Supply on demand**	**Availability**
Access	**Physical availability**	**Quality (health)**
Optimal water utilization	**Satisfy on demand**	**Cost effectiveness**

Source: own proposal.

Further theoretical reflections and research are necessary in the context of the dynamic changes in social, environmental and ecological systems and the implications that adaptive action has for resource-using sectors and the environment. A more holistic nexus framework enhances the ability to manage environmental interactions, human activities and policies in order to adapt to the uncertainties associated with global change, which have recently intensified. However, with the conceptualizations of the W–E–F nexus becoming increasingly complex and incorporating a plurality of various data, comprehensive quantitative analyses of dependencies and interactions grow more difficult. It can be found that most nexus analyses were conducted at regional or national levels, and their scope was highly dependent on the availability of data, national-level policy goals and metrics [35].

The above-mentioned elements are directly or indirectly linked to the W–E–F (water–energy–food) nexus, a concept that is still developing and expanding its boundaries. The term W–E–F nexus rose to prominence in the past decade due to the speech of the Secretary General of the United Nations, Ban-Ki Moon, during World Water Day in March 2011. He noted that the interconnections between water, energy and food are among the greatest challenges that mankind faces. The term nexus means “to connect” and conveys interactions between two or more elements and their dependencies or interdependencies. In the first definitions of the term ‘nexus’ in the Oxford Dictionary [36], the nexus between industry and political power and a nexus of interests, including, lately, “interactions and interconnections among different sectors (or subsystems) considering food, energy and water”, are mentioned.

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