The Contribution of Input-Output Multi-Objective Optimization Model of Sustainable Consumption and Production in Food-Energy-Water Nexus

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Abstract

Food, energy and water are essential for human survival. These resources consume each other thus enhancing security in one resource can reduce security in another resource. Multiobjective optimization approaches have been used to understand the complexity associated with the Food, Energy Water (FEW) Nexus. However most of these approaches focus on either maximizing resource production or minimizing resource consumption in the FEW Nexus but not addressing the two simultaneously. To achieve sustainability of the FEW Nexus sustainable consumption and production of the resources need to be emphasized. In this paper, the Input-Output theory is used to develop a multiobjective optimization model that minimizes resource intensities. Minimizing resource intensities results into minimized consumption and maximized production of resources in the nexus. Using the developed model simulations are carried out to demonstrate its applicability in FEW Nexus. The results show that the model can be used to explore alternative ways of minimizing consumption and maximizing production simultaneously based on the concept of non-dominated solutions.

Keywords: Input-Output Theory, Food-Energy-Water Nexus, Multiobjective Optimization Model, Sustainable Consumption and Production

Introduction

Sustainable consumption and production in Food, Energy and Water nexus has a direct or indirect link in achieving many if not all of the Sustainable Development Goals developed by United Nation. Many countries are concerned about addressing Sustainable Development Goals in the midst of pressures emanating from rapid population growth and climate change. The FEW nexus approach is one that can be used to address the challenges of ever growing demand for food, energy and water. This nexus depicts some complex interactions with hidden feedback connections among food, energy and water resources. The production of a specific resource requires the consumption of one or the two other resources thus playing a big role in determining the demand, supply and availability of the resources in the FEW Nexus. In relation to attaining global sustainability, managing the FEW Nexus has become a big challenge. This is due to the fact that increasing security of one resource may have a negative consequence on another resource. The purpose of this study is to design a multi-objective optimization algorithm based on Input-Output model.

Food, energy, and water resources are crucial for the survival of human beings and the systems involved in the production and consumption of these resources are tightly linked (Yuan and Lo, 2020). The FEW nexus is a term used to depict the complex interactions occurring between food, energy and water systems. The nexus is important in understanding existing interdependencies between the three resources (Itayi, Mohan and Saito, 2021). Climate change, urbanization and population are well known stressors that influence and also are influenced by the FEW nexus (Lange, 2019). Therefore, there is a need to develop adaptation and mitigation strategies to cope with the negative impacts of these stressors. One such strategy is to ensure sustainable consumption and production patterns that is formulated as goal 12 of Sustainable Development Goals(SDGs) (United Nations, 2015).

In FEW nexus water is consumed to produce energy and food, energy is consumed to produce water and food, food is consumed to produce energy. There exist some studies that have discussed measurements relating to the consumption and production in the FEW nexus. For instance, water consumption in energy production (Gerbens-Leenes, Hoekstra and Van der Meer, 2009; Chang *et al.*, 2016), water consumption in food production (Gerbens-Leenes, Mekonnen and Hoekstra, 2013), energy consumption in water production (Mo *et al.*, 2011; Gu *et al.*, 2016), energy consumption in food production (Carlsson-Kanyama, Ekström and Shanahan, 2003; Chang *et al.*, 2016; Gellings and Parmenter, 2016) and food consumption in energy production (Campbell *et al.*, 2008; Zhuang *et al.*, 2011; Bryngelsson and Lindgren, 2013). The weakness of these studies is that they are very general and do not provide specific measurements relating to consumption and production in a specific scale.

Sustainable consumption and production is about using less to produce more. This can be achieved by devising ways of enhancing efficiency in consumption and production of resources in the FEW nexus. Simultaneous minimization of consumption and maximization of production normally leads to high efficiencies. Therefore, a resource use intensity tends to be minimized if the amount of that resource consumed to produce one unit of another resource is reduced. Input-Output Theory is used to address the concept of a resource being consumed to produce another resource (Ebiefung and Kostreva, 1993; Dietzenbacher and Lahr, 2004) .It has been used to compute resource intensities and allocations in FEW nexus (Karnib, 2017a, 2018).

In FEW nexus, minimizing resource consumption and production is a multiobjective optimization task (Okola *et al.*, 2019). Several studies have been done to demonstrate the applicability of multiobjective optimization approaches in FEW nexus. For instance, there is an approach that minimizes costs associated with water, food and energy production as well that of reducing carbon dioxide emission.(Zhang and Vesselinov, 2017). Similarly a framework has been developed to minimize costs associated with consumption of water and energy in order to maximize food production (Karnib, 2017b). A multiobjective optimization approach has also been employed to assist in maximizing the electricity generated through hydropower while minimizing water reduction (Uen *et al.*, 2018). A reliability index is used to quantify each resource demand and supply in FEW nexus. Henceforth, the three indexes are maximized simultaneously (Wicaksono and Kang, 2019). A similar approach maximized a derived WEF nexus index to identify a cropping pattern that is optimized (El-Gafy, Grigg and Waskom, 2017). A nonlinear multiobjective optimization approach has been proposed to facilitate simultaneous maximization of benefits achieved from groundwater use and to minimize the destruction of resources associated with groundwater production. Therefore, the approach is able to depict the tradeoffs that occur in food, energy and groundwater production (Radmehr, Ghorbani and Ziaei, 2021).

Based on the few highlighted multiobjective optimization approaches, to the best of our knowledge none has emphasized on how to simultaneously minimize the resource consumption intensities in FEW nexus. The main goal of FEW nexus management tools is to identify synergies and tradeoffs that occur during complex interactions between systems linked in and to the nexus thus enhancing strategies used in resource allocations (Borge-Diez, García-Moya and Rosales-Asensio, 2022). Therefore, in this study an approach has been proposed that simultaneously minimize several resource intensities thus assisting the decision maker to identify synergies and trade-offs from the many non-dominated solutions obtained.

Input-Output Theory in Few Nexus

Input-Output Theory

The Input-Output theory specifies interrelationships among various industrial sectors, households, and government agencies in such a way that the output of an industry will appear as input distribution to other industries (Dietzenbacher & MLahr, 2004; Ebiefung & Kostreva, 1993). In this study we apply the Q-Nexus Model that consists of inter resource consumption quantities denoted by Z, final demand quantities denoted by y and the total of the two denoted by x (Karnib, 2017a). Equations 1 is used to formulize the model.

$$Z + y = x \qquad (1)$$

The Leontief Input–Output model specifies quantitative relationships between the inputs consumed and the outputs produced in a sector using linear equations. To achieve sustainability in the FEW Nexus, resource consumption and production need to be optimized simultaneously thus conflicting each other.

Resource Consumption and Production

In the FEW Nexus the main resources consuming each other are Food, Energy and Water. These resources can be broken down into specific types of food, energy and water (Karnib, 2017; Wicaksono et al., 2019).

i. Water resources include Surface water in rivers, lakes and reservoirs (W_1); Groundwater (W_2); Desalinated water from oceans (W_3); Others (W_4).

ii. Energy resources include Electricity (Wind) (E_1); Electricity (Hydro) (E_2); Biofuels (E_3); Electricity (Fossil Fuels) (E_4); Imported Electricity (E_5); Electricity (Solar) (E_6);

iii. Food resources include Fruits (F_1); Roots and Tubers (F_2); Cereals (F_3); Vegetables (F_4); Animal Products (F_5).

Based on the Input-Output theory and the Q-Nexus Model, the consumption and production of resources in FEW nexus are represented using Table 1.

Table 1: Resource Consumption in Producing Another Resource

	Inputs from the producing resources			
Total output of the resources	**water(w)**	**energy(e)**	**food(f)**	**demand**
water(w)	water-water(ww)	water-energy(we)	water-food(wf)	water-demand(wd)
energy(e)	energy-water(ew)	energy-energy(ee)	energy-food(ef)	energy-demand(ed)
food(f)	food-water(fw)	food-energy(fe)	food-food(ff)	food-demand(fd)

Table 1 is also formulated using equation 2 to 4

$$w = ww + we + wf + wd \quad (2)$$

$$e = ew + ee + ef + ed \quad (3)$$

$$f = fw + fe + ff + fd \quad (4)$$

Objective Functions

The consumption of a resource to produce one unit of another resource is known as resource intensity coefficient. The water-energy, water food, energy-water, energy-food and food-energy intensity coefficients are given using equations 5 to 9. In this case we assume that the amount used to produce water and the amount of food used to produce water is zero. These five equations also represent minimised objective functions.

$$a_{we} = we/e \quad (5)$$

$$a_{wf} = wf/f \quad (6)$$

$$a_{ew} = ew/w \quad (7)$$

$$a_{ef} = ef/f \quad (9)$$

$$a_{fe} = fe/e \quad (10)$$

Simulations

Simulations were facilitated in MATLAB using gamultiobj function. This function allows the components of a Multiobjective Optimisation Problem(MOP) to be combined. These components include objective functions, constraints, lower and upper bounds. Multi-objective optimization approaches can be used to address conflicts in the FEW Nexus because they are known to deal with multiple conflicting real world problems. These approaches provide non-dominated solutions that identify tradeoffs and synergies in FEW Nexus. They have a great potential in solving multi-objective optimization problems. They evolve solutions in each generation thus being able to produce non-dominated solutions which are closer to the Pareto-front.

Simulations are based on the Business As Usual (BAU) resource consumption and production data obtained from the work of (Karnib, 2018) as indicated in Table 2. This data is set to be the values for the lower bound vector. The upper bound vector values are set to either BAU values or to infinity. Therefore, we perform simulations based on the BAU settings for the lower bound and infinity values for upper bound values. The results obtained are used to compare the intensity coefficients for each resource obtained from BAU situations and those obtained after optimization.

Results and Discussion

The results obtained from the simulations demonstrated different ways of attaining sustainable consumption and production. The purpose of the simulation was to demonstrate how consumption and production change when the final demand is changing and resource intensities are minimized simultaneously.

The gamultiobj algorithm generated 78 non-dominated solutions that represented various alternatives of decision making. Only five solutions out of 78 were considered for analysis. For a solution to be selected its resource intensity has to be the one with the lowest value among the 78 solutions generated. For instance, the second row of table 3 indicates the lowest value of water-E1 intensity for a solution where water-energy intensity was the minimum among the 78 solutions. In this scenario the water consumption to produce E1 has increased from 60.000 to 60.055 but the intensity is the same as the one for the BAU scenario that has a value of 0.02502. Water production has also increased from 1900.00 to 1914.39 as indicated in Table 7. If row 5 of table 3 is considered, the lowest water intensity of 0.48494 is for producing F2. The amount of water consumption to produce F2 has increased from BAU value of 171.00 to 171.40 and also the water production has increased from a BAU value of 1900.000 to 1909.060 has shown in Table 7. The same kind of patterns can also be observed with energy consumption in production of water and food as well food consumption in production of energy.

The resource intensities indicated on Table 3 demonstrate alternative options that can be identified by the decision maker in relation to matters of resource consumption and production in FEW nexus. For instance, a sustainable consumption and production pattern can be identified as the one where a resource intensity is reduced, the amount consumed to produce another resource has a slight increase as compared to BAU value and the total production of the resource has a large increase as compared to the BAU values.

Table 2: Resource Consumption in FEW Nexus

	W1	W2	W3	W4	W5	E1	E2	E3	E4	E5	F1	F2	F3	F4	F5	Y1	Y2	Y3	Y4	Y5	Y6
W1	0	0	0	0	0	40	110	20	0.5	1	120	110	100	180	300	30	1	4	28	0	1
W2	0	0	0	0	0	20	30	0	0.5	1	65	55	60	90	150	154	2	16	146	0	2
W3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	12	4	0	0
W4	0	0	0	0	0	0	1	0	0	0	5	5	5	5	5	0	0	0	0	0	0
W5	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	0	0	0	0	0	0
E1	10	12	10	5	5	0	0	0	0	0	100	60	70	80	150	1000	90	336	470	0	0
E2	80	110	25	2	1	0	0	0	0	0	40	20	30	30	70	1400	160	1071	465	0	0
E3	1	1	2	0	0	0	0	0	0	0	5	5	5	5	5	50	5	30	15	0	0
E4	1	2	1	1	1	0	0	0	0	0	0	0	0	0	2	1	0	4	0	0	0
E5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60	0	0	0	0	0
F1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	80	1	10	1	2	50
F2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	228	0	10	2	10	102
F3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	600	1	225	0	2	26
F4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	2	72	2	40	292
F5	0	0	0	0	0	0	0	0	0	160	0	0	0	0	15	2000	200	300	100	60	789

Table 3: Water Intensities in Energy and Food Production

Water	E1	E2	E3	E4	E5	F1	F2	F3	F4	F5
WconBAU	0.02502	0.04024	0.15504	0.07692	0.03333	1.26490	0.48580	0.19393	0.54528	0.12610
WconWEmin	0.02502	0.04058	0.15210	0.27189	0.06329	1.25401	0.48902	0.19420	0.54670	0.12635
WconWFmin	0.02502	0.04063	0.15504	0.30744	0.06282	1.25593	0.48545	0.19393	0.54361	0.12610
WconEWmin	0.02672	0.04151	0.18538	0.13707	0.07561	1.31742	0.49963	0.20427	0.54493	0.12846
WconEFmin	0.02503	0.04070	0.15296	0.30709	0.06406	1.25425	0.48494	0.19409	0.54454	0.12612
WconFEmin	0.03202	0.04607	0.11688	0.14083	0.32543	1.00409	0.52580	0.22663	0.55001	0.13874

Table 4: Water Consumption in Energy Production

Water	E1	E2	E3	E4	E5
WconBAU	60.00000	141.00000	20.00000	1.00000	2.00000
WconWEmin	60.05516	142.36300	20.01827	4.08193	3.79890
WconWFmin	60.00000	142.35046	20.00000	4.07840	3.76944

WconEWmin	64.34103	145.87813	28.03132	4.16328	4.64557
WconEFmin	60.04082	142.65386	20.00340	4.15245	3.84508
WconFEmin	82.62565	168.57551	32.14853	17.38637	22.04613

Table 5: Water Consumption in Food Production

	F1	F2	F3	F4	F5
WconBAU	191.00000	171.00000	166.00000	277.00000	457.00000
WconWEmin	191.52346	172.90412	166.29951	278.86418	458.10222
WconWFmin	191.00000	171.00000	166.00000	277.00391	457.00000
WconEWmin	202.86205	178.91629	176.03808	283.05384	467.28074
WconEFmin	191.20968	171.40068	166.36794	277.24471	457.31991
WconFEmin	212.00274	208.91059	211.07518	310.35453	513.16323

Table 6: Final Demand for Water

	Y1	Y2	Y3	Y4	Y5	Y6
WconBAU	198.00000	3.00000	32.00000	178.00000	0.00000	3.00000
WconWEmin	198.13618	3.43253	33.63530	178.13705	0.00000	3.03897
WconWFmin	198.00000	3.00000	32.00000	178.00000	0.00000	3.00000
WconEWmin	201.46136	14.15120	35.58840	190.03563	0.00000	3.23605
WconEFmin	198.04670	3.21388	32.35969	178.15123	0.00000	3.04971
WconFEmin	219.30587	16.33831	65.74654	211.75857	0.00000	25.22890

Table 7: Water Production

WATER	TOTAL PRODUCTION

WconBAU	1900.0000
WconWEmin	1914.3908
WconWFmin	1906.2022
WconEWmin	1999.6830
WconEFmin	1909.0597
WconFEmin	2316.6667

Conclusion

The proposed model has capability to provide various scenarios that can identify synergies and tradeoffs in FEW nexus. Therefore, the non-dominated solutions given by the algorithm are considered as alternatives of optimization of resource consumption and production in the FEW Nexus. These solutions are creating multiple sustainable consumption and production patterns hence enabling policy and decision makers to meet the goal number 12 of SDGs.

From the available literature, it is clear that water consumption has been increasing and yet Over 2 billion people are situated in countries with high level of water stress. Also households' consumption of energy contributes 21% of carbon dioxide emissions. There is evidence showing that degradation of natural resource bases is leading to a decrease in food supply. All such issues can be addressed by formulating policies that are integrative in order to achieve a sustainable consumption and production situation. We therefore need effective tools that can be used to support policy and decision making processes hence avoiding resource wastage or over use. This will mainly address target 12.2 which states that "By 2030, achieve the sustainable management and efficient use of natural resources".

To the best of our knowledge existing approaches are not able to demonstrate ways of how to minimize the resource intensities simultaneously hence they have failed to generate several patterns that depict scenarios that can lead to sustainable consumption and production in FEW nexus. In future a novel Many Objective Optimization algorithm will be developed to handle five or more objectives in an effective way.

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