International Journal of
Operations Research

International Journal of Operations Research Vol. 18, No. 3, 67-77 (2021)

Realization of Circular Economy in the Food–Energy–Water Nexus Through Tuning Input-Output Matrix : An Optimization Approach

Yi-Ting Chiu[1], Yu-Ching Lee[2], Hsiao-Fan Wang[3*]

[1,2,3*]National Tsing Hua University, 101, Section 2, Kuang-Fu Road, Hsinchu 300044, Taiwan, ROC

Received February 2021; Revised April 2021; Accepted September 2021

Abstract: Although considerable progress has been achieved in science, technology, and living standards, the accompanying environmental destruction and scarcity of resources cause the awareness of sustainable economic development. Circular Economy (CE) has been recognized as a promising solution. In the past, any national policies regarding economic development were to use the existing industry structure to analyze the relationship and correlations among industries. However, to predict the potential increment on the value-added of a prospective policy as implementing CE, re-evaluation of the industry structure is necessary. In this study, a nonlinear optimization model was established to provide a novel industry input-output structure that can balance the supply and demand while waste is avoided, the economic benefits remain maximized. The proposed model focused on food, energy, and water as a FEW Nexus because food, energy, and water are the required living resources. The results reveal that apart from the suggested development of renewable energy, the proposed industry structure can not only achieve a closed-loop FEW Nexus but also considerably promote the economy. A case study of the Taiwan economy was provided for illustration.
Keyword — Circular Economy; Food-Energy-Water Nexus (FEW Nexus); NLP; Leontief's Equilibrium Theory; Taiwan Domestic Economy.

1. INTRODUCTION

With population growth, technological progress, and improvements in the living standards, extensive environmental damage has occurred. Therefore, sustainable development has drawn a great attention. The Ellen MacArthur Foundation (2014) proposed that the establishment of circular economy is a promising approach to achieving sustainable global development. Transforming the economy from a linear to a circular economy can reduce utilization of resources and wastage.

In the circular economy, three fundamental resources, namely food, energy, and water (FEW), are critical. These are indispensable basic resources for human survival and development. Moreover, these resources are strongly related to each other and form a nexus. For example, a large amount of energy is required in food production; food waste can be used for biomass energy production; flowing water is the main source of power generation for hydroelectric power plants, whereas heated boiling water is a source of heat energy; and agriculture requires water in large quantities. Therefore, effective supply and demand management of these resources is essential.

To assess the inter-industrial exchanges, Leontief's input-output model has been widely used (Metzler (1951); Toroptsev, Marakhovskii, and Duszynski (2019)). Many studies used the published governmental input-output accounts, which is the matrix set of inter-industry exchanges, as a benchmark of the further analysis. Regarding the policy of implementing a prospective circular economy, it is usually necessary to pre-estimate the industry structures before an actual input-output matrix is published by the government through regular way of actual data collection. In addition, although circular economies attract considerable attention, inadequate governmental support is a major obstacle that hinders restructuring of industrial activities (Rizos et al. (2016); Schanes, Dobernigab, and Gözet (2018)). Therefore, this study proposed a novel FEW nexus model by tuning existing Leontief's input–output model and establish an effective demand and supply industrial network. Based on the proposed industrial cooperation, the zero-waste and profitable economy with maximal overall value added can be achieved.

The rest of this paper is structured as follows: Section 2 presents a review of related literature. Section 3 defines the problem and introduces the mathematical model. Section 4 presents a case study of the Taiwan economy. Section 5 conducts the parameter analysis to verify the solution, and the conclusion is drawn in Section 6.

*Corresponding author's e-mail: hsiaofanwang@gmail.com

http://doi.org/10.6886/IJOR.202109_18(3).0002

2. LITERATURE REVIEW

Human activity has adversely affected the environment and strained global resources. Therefore, green supply chain management, in particular, closed-loop logistics, has attracted considerable attention (e.g. Wang and Hsu (2010), Govindan and Soleimani (2017)). However, closing a single industry's resource cycle is costly and ineffective, thereby resource recycling between more than two industries has been proposed as a promising approach for achieving global resource sustainability as so-called Circular Economy (Ellen MacArthur Foundation (2014)). The closed resource cycle is through a cyclic flow of resources between reuse and production among different industries, industrial symbiosis is a typical example (Bocken, De Pauw, Bakker, and Van Der Grinten (2016)).

An equitable distribution of FEW resources can be obtained through effective management of the FEW nexus (Hu, Fan, Huang, Wang, and Chen (2019); Pagotto and Halog (2016); Schneider and Avellan (2019)). Population growth and climate change have resulted in increased FEW scarcity (Wicaksono, Jeong, and Kang (2017)). Therefore, promoting a circular economy of these three resources can considerably ease the pressure on global resources. Albrecht, et al. have given a comprehensive review on the research approaches of FEW (Albrecht, Crootof, and Scott (2018)). Since we intend to support decision on industry policy from a nation-wide viewpoint, therefore, investigation of industry structure would be our basic approach and is the focus of our study.

Although circular economy is being promoted, obstacles, such as existing corporate culture toward the environment, inadequate funding, and inadequate government support, information, technical knowledge, and technical support, may limit its adoption by small and medium enterprises (Rizos et al. (2016)). Above all, government support plays a crucial role in guiding industries toward a circular economy. For instance, the government may formulate regulations on rewards and punishments. Rewards in the form of incentives can be planned for companies to promote a circular economy. Industries often passively defer to legal regulations before undertaking activities that do not benefit them. Therefore, governments should actively promote circular economy. The results of this study can assist governments in policy making.

Lin and Chang (2004) used Leontief's input-output model (I-O Model) to calculate the value added created by primary agricultural products and related food sectors from 2000 to 2003. Because most of governments conduct a regular national survey and establish an input-output table to reveal the national industrial structure, therefore, many studies related to industry associations have proposed various applications to determine the forward and backward relevance of industries (Hirschman (1958); Rasmussen (1956); Wang and Hsu (2014)). In Taiwan, the government conducts such survey every five years, and provides different scales of industry I-O tables. The nearest time is 2016 and next time will be at 2021 (Statistic Bureau, Taiwan (2016)). The government has already organized and merged all the industries in advance for different application purposes. For example, the industry I-O table in 2016 has been merged from 128 industries into 63 industries, of which energy sector includes all energy-related industries from electricity, steam, and gas supply.

However, for overall industrial strategic planning, a government is required to draw a development blueprint for enterprises to follow (Schanes et al. (2018)). Therefore, we proposed an innovative approach based on Leontief's economy equilibrium theory to analyze the FEW nexus and establish an effective demand and supply industrial network to achieve a zero-waste and profitable economy. The proposed model can assist governments in framing relevant policies for achieving a circular economy. In addition, a case study of Taiwan's domestic economy based on FEW nexus is discussed in subsequent sections.

3. RESEARCH METHOD

From the above analysis, in this section, we shall develop an analytical model that can balance the supply and demand of the FEW industries and enhance the overall economy.

Based on the input-output table presented in Fig. 1, the Leontief equilibrium model is expressed in (1) - (3), of which, from the production view point, the total domestic production of each industry, j, equals to the intermediate production plus the value-added as shown in (1) below. Also, from demand view point, the total domestic demand equals to the intermediate demand and the final demand as shown in (2) below. If considering the import-export, based on supply-demand equilibrium theory, the total demand equals to the total domestic production plus the import as shown in (3) below. The proposed model in a form of nonlinear program is developed that is a production-specific analytical model focused on the FEW Nexus.

Industry input \ Industry output			Intermediate output: Industries 1	j	n	Total intermediate output	Final demand	Total demand	Supply: Import	Supply: Domestic production
Intermediate input	Industries	1	x_{11}	x_{1j}	x_{1n}	$\sum_{j=1}^{n} x_{1j}$	F_1	D_1	A_1	X_1
		i	x_{i1}	x_{ij}	x_{in}	$\sum_{j=1}^{n} x_{ij}$	F_i	D_i	A_i	X_j
		n	x_{n1}	x_{nj}	x_{nn}	$\sum_{j=1}^{n} x_{nj}$	F_n	D_n	A_n	X_n
Total intermediate input			$\Sigma_{i=1}^{n} x_{i1}$	$\Sigma_{i=1}^{n} x_{ij}$	$\Sigma_{i=1}^{n} x_{in}$	$\sum_{i,j=1}^{n} x_{ij}$	$\sum_{i=1}^{n} F_i$	$\sum_{i=1}^{n} D_i$	$\sum_{i=1}^{n} A_i$	
Value-Added			V_1	V_j	V_n	$\sum_{j=1}^{n} V_j$				
Domestic production			X_1	X_j	X_n					$\sum_{i,j=1}^{n} X_{i=j}$

Figure 1: Leontief's Input-Output Table

$$\sum_{i=1}^{n} x_{ij} + V_j = X_j \qquad \forall j \in J \tag{1}$$

$$\sum_{j=1}^{n} x_{ij} + F_i = D_i \qquad \forall i \in I \tag{2}$$

$$D_i = X_i + A_i \qquad \forall i \in I \tag{3}$$

where	
$i \in I, j \in J$	$i, j = 1, 2 \ldots n$ the number of industries
Notations	**Explanation (unit: million NT dollars)**
x_{ij}	the transfer amount from industry i to industry j
$X_{i=j}$	domestic production for industry $i(j)$
V_j	the amount of value-added for industry j
F_i	the amount of final demand for industry i
D_i	the amount of total demand for industry i
A_i	the amount of import for industry i

To focus on FEW nexus, a given input-out model is consolidated in Section 3.1. Then, by defining the measurement in Section 3.2 and stating the assumptions in Section 3.3, the model is proposed in Section 3.4.

3.1 Consolidating Industrial Input-Output Table

In the industrial I-O table, we only focused on FEW industries. So, from the production perspective we consolidate original I-O table into a new form as shown in Figure 2 (Chiu, Lee, and Wang (2020)):

1st. The agricultural industry, livestock industry, and fisheries were categorized as "the food industry" in the industry I-O table denoted by $j = 2$;

2nd. Electricity, steam and gas supply were categorized into "the energy industry" as $j = 3$;

3rd. Tap water was categorized as "the water industry" as $j = 4$;

4th. The rest of the industries were categorized into the "other industries" category as $j = 1$;

5th. To promote renewable energy, we added a "renewable energy industry," which did not exist in the original industry I-O table as $j = 5$.

3.2 Measurement of Value Added

The growth rate (4) has shown to be used effectively in measuring the value added of individual industries (Chiu et al. (2020)). Therefore, we used the growth rate as an indicator in the following model and case study.

$$\frac{\text{The former year's } V - \text{ the older year's } V}{\text{the older year's } V} \leq \textit{New growth rate} \leq \frac{\text{The nearest year's } V - \text{ the former year's } V}{\text{the former year's } V} \tag{4}$$

where $\textit{New growth rate} = \dfrac{\text{New } V - \text{the nearest year's } V}{\text{the nearest year's } V}$

3.3 Assumption

Wicaksono et al., have shown that the transformation of food to nonrenewable energy is limited and can be neglected, it is assumed to be zero (Wicaksono et al. (2017)).

Input \ Output	Other industries ($j = 1$)	Food industry ($j = 2$)	Energy industry ($j = 3$)	Water industry ($j = 4$)	Renewable energy industry ($j = 5$)	Intermediate output
Other industries ($j = 1$)	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	$\sum_{j=1}^{5} x_{1j}$
Food industry ($j = 2$)	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	$\sum_{j=1}^{5} x_{2j}$
Energy industry ($j = 3$)	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	$\sum_{j=1}^{5} x_{3j}$
Water industry ($j = 4$)	x_{41}	x_{42}	x_{43}	x_{44}	x_{45}	$\sum_{j=1}^{5} x_{4j}$
Renewable energy industry ($j = 5$)	x_{51}	x_{52}	x_{53}	x_{54}	x_{55}	$\sum_{j=1}^{5} x_{5j}$
Intermediate input	$\sum_{i=1}^{5} x_{i1}$	$\sum_{i=1}^{5} x_{i2}$	$\sum_{i=1}^{5} x_{i3}$	$\sum_{i=1}^{5} x_{i4}$	$\sum_{i=1}^{5} x_{i5}$	$\sum_{i,j=1}^{5} x_{ij}$
Value-added	V_1	V_2	V_3	V_4	V_5	$\sum_{j=1}^{5} V_j$
Domestic Production	X_1	X_2	X_3	X_4	X_5	Unit: million NT dollars

Figure 2: Consolidated Industrial Input-Output Table from the Production Perspective

3.4 The Proposed Model

To overcome the problem described in the previous sections, we developed a mathematical nonlinear optimization model with the following notations:

Table 1: Definition of Indices, Variables and Parameters

Indices	Explanation
$j \in J$	output industries $j = 1$, Other industries, $j = 2$, Food industry, $j = 3$, Energy industry, $j = 4$, Water industry, $j = 5$, Renewable energy industry.
Decision Variables	Explanation
a_{ij}	the ratio of industry i input to industry j
v_j V_{ij}	the ratio of value-added for industry j, $j = 1, 2, 3, 4$ the amount of value-added for industry j, $j = 1, 2, 3, 4$ (unit: million NT dollars)
e X_S	the ratio of renewable energy based on the energy industry the amount of the input of renewable energy industry (unit: million NT dollars)
Parameters	Explanation
X_j v_S O_j	the amount of original input of industry j, $j = 1, 2, 3, 4$ (unit: million NT dollars) the ratio of value-added in renewable energy industry raw materials of value-added from industry j in the nearest year, $j = 1, 2, 3, 4$ (unit: million NT dollars)
U_j^R L_j^R	the upper bound of growth rate of value-added for industry j, $j = 1, 2, 3, 4$ the lower bound of growth rate of value-added for industry j, $j = 1, 2, 3, 4$

FEW Nexus Model

To robustly maximize the value added of all industries is equivalent to maximize the value added of an industry with the minimum value added. Therefore, the objective function is formulated by (5) as below:

$$\text{Max}(\min_j V_j) \tag{5}$$

Subjective to

$$V_j = X_j v_j \qquad \forall j \in J \tag{6}$$

$$\sum_{i=1}^{5} a_{ij} = 1 \qquad \forall j \in J \tag{7}$$

$$a_{34}X_4 + a_{54}X_4 + a_{24}X_4 \geq a_{42}X_2 + a_{45}X_5 \tag{8}$$

$$a_{32}X_2 + a_{52}X_2 + a_{42}X_2 \geq a_{25}X_5 + a_{24}X_4 \tag{9}$$

$$a_{25}eX_3 + a_{45}X_5 + (1 - e)X_3 \geq a_{32}X_2 + a_{34}X_4 + a_{54}X_4 \tag{10}$$

$$X_5 - eX_3 = 0 \tag{11}$$

$$0 \leq e \leq 1 \tag{12}$$

$$a_{23} = 0 \tag{13}$$

$$L_j^R \leq \frac{(V_j - O_j)}{O_j} \leq U_j^R \qquad \forall j \in J \tag{14}$$

$$v_j,\ a_{ij},\ V_j,\ X_5 \geq 0 \qquad \forall i \in I,\ \forall j \in J \tag{15}$$

Constraint (6) defines the relation of value added between amount and ratio. Constraint (7) is Leontief's input/output equation from the aspect of domestic gross supply. That is the gross production is closed by the intermediate input plus value added. Constraints (8) – (10) ensure the closed circulation of a FEW Nexus under the condition of the supply more than the demand for each industry. To promote green energy, constraint (11) shows a strategic policy for the relationship of shifting from non-renewable energy to the renewable energy of which the shifting ratio is defined by (12). Constraint (13) is based on assumption 1 that the transfer ratio from the food industry to the non-renewable energy industry is zero. Constraint (14) measures the required economic development of each industry's value added by the growth rate.

3.5 Summary and Discussion

In this section, we provide a model of FEW Nexus based on Leontief's I-O model to achieve a closed-loop resource cycle to reduce unnecessary wastage. The model can assist the government to enhance the value added of all concerned industries by increasing the value added of the weakest industry. Because our model has 30 variables but only 20 constraints, multiple optimal solutions exist, which provides the government the flexibility in framing alternative policies for a new industry structure with the same goal achievement. A case study of the FEW Nexus of the Taiwanese domestic economy is shown in the following.

4. CASE STUDY

A case study of the Taiwanese domestic economy was used to validate the proposed model. Based on our FEW Nexus, we measured the value added of individual industries by calculating their growth rates. To support the decision from the multiple optimal solutions, a set of initial points based on the most recent I-O data of year 2016 was adopted (Statistic Bureau, Taiwan (2016)). However, there is no renewable energy industry in 2016. Based on the analysis of the industrial linkage of green energy and the petrochemical industry, value added of renewable energy is assumed to be 25% in our case study (Hong et al., 2011). The consolidated tables of years 2006, 2011, and 2016 were used for calculating the growth rates.

The software Ampl/Knitro (Artelys Knitro (2015)) was employed to execute the model and compare the results with the original data from 2016, which is shown in Table 2 with input-output matrix $[a_{ij}]$, value added $[v_j]$ and total value-added V, ratio of renewable energy, e, amount of renewable energy and exiting energy industry.3

Table 2: Preliminary Output of the Proposed Model with the Comparison of the Data of 2016

$a[*,*]$:=						
:	1	2	3	4	5	
1	0.08861	0.14577	0.16150	0.00000	0.16503	
2	0.08959	0.14911	0.00000	0.00000	0.25492	
3	0.08959	0.15646	0.16129	0.00000	0.16503	
4	0.08959	0.00000	0.18329	0.00000	0.00000	
5	0.08765	0.21974	0.18408	0.00000	0.16503	
$v[*]$:=						
1	0.55497					
2	0.32893					
3	0.30984					
4	1.00000					
5	0.25000					
V = 44807						
e = 0.82763						
X_5 = 571738						
x_new3 = 119076						
Industry (j)	Other Industries (1)	Food Industry (2)	Energy Industry (3)	Water Industry (4)	Renewable Energy Industry (5)	Renewable Energy Ratio (e)
Comparison of the Model	+0.08899	+0.14193	+0.00647	+0.04393	+0.25000	15.13%

4.1 Analysis and Discussion

The results revealed that the lowest amount of value added (v) is NT 26,123.3 million dollars (X_4v_4), which comes from the water industry. In Table 2, it can be noted that although the value added ratios are all larger than those of 2016 data with a positive sign "+" , the suggested ratio of renewable energy with respect to the original nonrenewable energy (e) was 15.13%, which did not satisfy the goal of Taiwanese government with increasing the use of renewable energy to 20% of the total energy by 2025. Therefore, the proposed industry structure should be further strengthened by incorporating the renewable energy industry in the model to satisfy the government's expectations and realize a circular economy.

5. PARAMETER ANALYSIS

We attempted to maximize the value added of the smallest industry to ensure that the value added of all industries improved. Improving the overall economy is a key measurement indicator for government policies. Therefore, in parameter analysis, we determined the largest overall value added to provide more comprehensive support.

Parameter analysis was designed by two subsequent phases. In the first phase, we used a growth rate $\pm$ one standard deviation (SD) for each industry as the lower bound and determined the lower bound that can achieve the best overall value added. In the second stage, based on the results of the first stage, the value added ratio of renewable energy which was referred to the current energy policy of 20% of total energy supply in 2025 (Energy Policy of Taiwan, 2016) to provide the suitable lower bound of value added. Then, the overall economy which brings out the new industry structure is presented.

5.1 Data Preparation for Parameter Analysis

When calculating the average and standard deviation of growth rates for all industries, considering that the overall economy fluctuates over time, the latest data have more reference value. Assuming the growth rate $R \sim \Gamma(\alpha, \beta)$, we used the Gamma function of (16) with the weight of (17) to calculate the mean and standard deviation (SD) of growth rates L_i^R as (18)-(19) (Windham (1995)), of which the growth rate $\pm$ SD is defined as the lower bound. Table 3 presents the weight of each year's growth rate based on the Gamma Function.

$$f(r_i) = \frac{r_i^{(\alpha-1)}\beta^{\alpha}e^{-\beta x_i}}{\Gamma(\alpha)} \qquad , \text{x} > 0 \tag{16}$$

$$Weight(w_i) = \frac{f(r)}{\sum_{i=1}^{5} f(r_i)} \tag{17}$$

$$Average(\bar{L_i^R}) = \frac{\sum_{i=1}^{5} w_i \times L_i^R}{\sum_{i=1}^{5} w_i} \tag{18}$$

$$StandardDeviation = \sqrt{\frac{\sum_{i=1}^{5} w_i \times (L_i^R - \bar{L_i^R})^2}{\sum_{i=1}^{5} w_i}} \tag{19}$$

$i = 0, 1 \ldots 5$ year of the data, w_i the weight of growth rate, L_i^R growth rate.

Table 3: Weight of the Growth Rates based on Gamma Function

$R \sim \Gamma(1,2)$	$f(r_i)$	w_i
$i = 0$ 2016 - 2011	0.5	0.41391
$i = 1$ 2011 - 2006	0.30327	0.25083
$i = 2$ 2006 - 2004	0.18394	0.15232
$i = 3$ 2004 - 2001	0.11157	0.09272
$i = 4$ 2001 - 1999	0.06767	0.05629
$i = 5$ 1999 - 1996	0.04104	0.03394

5.2 First Stage: for Each Industry

In the first stage, for each industry, we used the original value added lower bound ± SD to perform parameter analysis. We determined the maximum total value added and the new industry structure that each industry can produce within a given lower bound and ranked the best overall value added of these industries. Table 4 lists a ranking of the maximum total value added from the four industries.

The results indicate that the energy industry provides the largest overall value added, and its lower bound is considerably higher than the original value added. In addition, according to our model, the energy industry (nonrenewable) and the renewable energy industry are closely related because their total amount was a fixed parameter value (the amount of domestic production in energy industry). Therefore, considering renewable energy as a prominent feature in government policies for promoting a circular economy, we used the new lower bound of the energy industry as 0.38555 and conducted parameter analysis of the value added of the renewable energy industry.

Table 4: Maximum Total Value Added from the Four Industries

Industry (j)	Other Industries (1)	Food Industry (2)	Energy Industry (3)	Water Industry (4)
Total value added (unit: million NTdollars)	20781586	20773062	20914388	20773159
Lower bound	0.22265	0.27061	0.38555	0.07326
Rank	2	4	1	3

5.3 Second Stage: for Renewable Energy Industry

In this stage, we changed the lower bound of the energy industry to 0.38555 based on the results of the first stage. According to the current policy (Energy Policy of Taiwan, 2016), we redefined the range of the value added ratio of renewable energy from the original 25% to 20%–30% and performed parameter analysis. Thus, in this analysis, the value added ratio of renewable energy started from 20% and increased by one unit, result in a new industrial structure. The final new industry structure was obtained by determining the largest total value added from the results. The results shown in Table 5, indicate that when the value added ratio of renewable energy is equal to 28%, the largest overall value added (NT$20,920,800) can be generated. Figure 3 displays the recommended industry structure when the value added ratio of renewable energy is equal to 28%. Therefore, development of renewable energy is highly recommended from the new industry structure.

Table 5: Results of the Second Stage of Parameter Analysis

$a[*,*]$:=					
:	1	2	3	4	5
1	0.08841	0.05414	0.06065	0.06138	0.14369
2	0.08841	0.05414	0.00000	0.06407	0.15855
3	0.08841	0.10789	0.06065	0.15483	0.14369
4	0.08841	0.02147	0.06065	0.06138	0.13040
5	0.08841	0.10789	0.06065	0.07531	0.14369
$v[*]$:=					
1	0.55794				
2	0.65449				
3	0.75740				
4	1.58302				
5	0.28000				
e = 0.24259					
V = 26123.3					
sum$V$ = 20920800					

5.4 Discussion

Through parameter analysis, we increased the lower bound of the original value added the energy industry and simultaneously obtained a better overall value added. Because multiple optimal solutions were obtained in the parameter analysis, we can provide more industry structures for the government. Fig. 3 presents the recommended industrial transfer structure of FEW industries. The closed loop of circulation with two directions of resource flows not only ensures the sustainability of the resources, but also create the largest total value added. Based on the analysis in the second stage, this new industry structure can enhance the overall value added to NT$20,920,800 million. Table 6 presents a comparison of value added between the data of 2016 and the data of parameter analysis. The value added of all industries increased considerably.

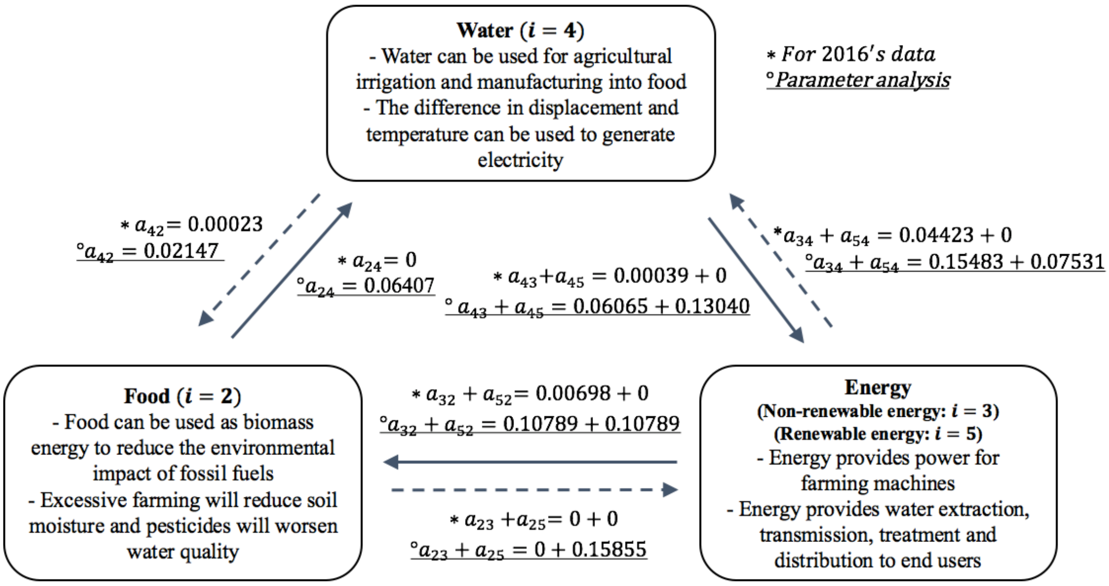

Figure 3: The Recommended FEW Circulation Structure

Table 6: Differences in Value Added Between the Data of 2016 and Parameter Analysis

Industry (j)	Other Industries (1)	Food Industry (2)	Energy Industry (3)	Water Industry (4)	Renewable Energy Industry (5)	Total value added
Data in 2016 (ratio form)	16503971 (0.45952)	328871 (0.52175)	296851 (0.42871)	24155 (0.53909)	0 (0.00000)	17153794 (0.46011)
Results of parameter analysis (ratio form)	20038800 (0.55794)	412538 (0.65449)	396293 (0.75740)	26123 (0.58302)	46924 (0.28000)	20920800 (0.56116)
The difference (ratio form)	+3534884 (+0.09842)	+83667 (+0.13274)	+99443 (+0.32769)	+1968 (+0.04393)	+46924 (+0.28000)	+3767006 (+0.10105)

Furthermore, from Figure 3, the establishment of a new industry structure based on a closed-loop FEW allows more resource flow among industries. According to the date of 2016, the food industry did not provide any resources to the water industry. In the new industry structure, resources worth NT$40,385 million were transferred from the food industry into the water industry. However, many agricultural plants require water in large quantities. Therefore, the government should focus on using related technologies to obtain more water resources. Furthermore, food and energy are closely related because a large amount of energy is consumed in food production. Conversely, waste food can also be reused to produce biomass energy. Due to the precious of food, the proportion of food as a renewable energy source is hardly to be counted. However, because of limited resources of oil, maximizing the use of renewable energy is crucial. Finally, from the date of 2016, NT$266 million of resources were transferred from the water industry to the energy industry. In the new industry structure, NT$10,312 million worth of resources (i.e., almost 39 times the original data) were transferred from the water industry to the energy industry. The resource transfer was less than the target value, and there is considerable scope of improvement in the future. Because water is a more stable renewable energy source than wind and solar energy, governments should focus on water projects, especially with abundant water resource of Taiwan.

The development of renewable energy is crucial when promoting a circular economy. Through the parameter analysis, we devised a novel industry structure with an increased proportion of renewable energy (24%). According to the results, the new industry structure not only increases the circulation of resources but also improves the overall economy. Therefore, in the future, based on this new industry structure, the government can encourage recycling of resources between industries and development of renewable energy to create environmentally friendly and prosperous economy.

6. CONCLUSION

It is sometimes falsely believed that sustainable development is not economic. In fact, sustainable development can improve resources circulation and in many successful applications, the macro economy and social welfare are both enhanced. In addition, the risk of resources shortage due to potential disaster can be largely reduced. To facilitate policy making about the circular economy, we provided a prospective industrial structure to realize the possible results of a circular economy. In particular, the structure focused on the FEW Nexus has improve the overall economy and reduce environmental impact.

We have developed a nonlinear programming model and used the growth rate as a measurement to maximize the overall economic value added when the FEW industries reach a balance between the supply and demand. A case study of the Taiwan domestic economy for the year 2016 was used for validating the new industry structure. The results revealed that the proposed industry structure can improve the overall value added to 1.2 times that of year 2016.

To demonstrate how to apply the results to decision support in order to reach the government goal of renewable energy development, we applied parameter analysis on the results of the case study to obtain a more desirable industry structure. By revising the lower bound of the value added of the energy industry, the proportion of value added of the renewable energy industry can be increased to 28% instead of 25% in the case study. Consequently, the new industry structure can improve the overall economy by 1.01 times that of the previous structure and achieved a 1.22 times improved economy than that of year 2016. The results of the parameter analysis revealed that the promotion of renewable energy is a crucial factor in the industry structure. Therefore, we provide some suggestions for the government to promote circular economies and renewable energy.

Based on the proposed model of circular economy, the resultant new industry structure can ensure the balance of the supply and demand among FEW industries and simultaneously improve the overall economy. Development of renewable energy is crucial to promote a circular economy in the FEW Nexus. Therefore, in the future, the Taiwan government should promote the circular economy based on the transfer structure establishing from this study (Fig.4). By increasing the transfer ratio of food, energy and water resources to the target value, the circular economy and economic growth can be improved. Since the government is the leader of policy-making, it can further set up a reward and punishment system, so that industries related to food, energy, and water will be more motivated to the promotion of circular economy. However, we aware that this new industry structure is a reference for policy-making. Several factors, such as implementation costs, coordination between departments, cooperation methods, and other challenges and difficulties, are not considered in the model. These challenges should be considered during actual implementation.

This research is by necessity limited by scope. Due to the late development of the renewable energy technologies in Taiwan, there was no recorded industries of renewable energy before 2016. However, we have aware the recent progress and significance of promoting different types of renewable energies by the Taiwan government. Therefore, we created a pseudo sector of renewable energy while we consolidated the I-O table as shown in Fig. 2. This allows our further study when the national survey is conducted in 2021. By then, separating solar energy, water energy, and biogas energy might provide more insights about renewable energy industry; and emerging technology such as producing biogas from food waste could be considered in our model to capture more sophisticated circulation among industries for further policy making.

The proposed nonlinear programming model was developed from the perspective of the producer. In the future, a model based on the perspective of consumers should be developed to compare with the model developed from the production perspective. An industry structure incorporating both perspectives would be beneficial to the environment and overall economy. Both approaches are our further studies.

ACKNOWLEDGEMENT

The authors acknowledge the financial support from the Ministry of Science and Technology of Taiwan, ROC with the project number 109-2221-E007-071-MY3.

REFERENCES

Albrecht, T. R., Crootof, A., & Scott, C. A. (2018). The water-energy-food nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*, *13*(043002).

Artelys Knitro. (2015). *Software ampl/knitro.* Retrieved from `https://ampl.com/products/solvers/solvers-we-sell/knitr`

Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *35*(5), 308-320.

Chiu, Y. T., Lee, Y. C., & Wang, H. F. (2020). *An approach to developing new industrial structure based on circular economy - a case of FEW nexus in Taiwan* (Unpublished master's thesis). Department of Industrial Engineering and Engineering Management, National Tsing Hua University.

Elbounjimi, M., Abdulnour, G., & Ait Kadi, D. (2015). A mixed integer linear programming model for the design of remanufacturing closed-loop supply chain network. *International journal of supply and operations management*, *2*(3), 820-832.

Ellen MacArthur Foundation. (2014). *Ellen macarthur foundation – rethink the future.* Retrieved from `http://www.ellenmacarthurfoundation.org/`

Executive Yuan, Taiwan. (2016). *Approach to non-nuclear country in 2025, a new energy policy.* Retrieved from `https://www.ey.gov.tw/Page/9277F759E41CCD91/c094fb4e-6c07-4a87-9435-fb97f11dde10`

Govindan, K., & Soleimani, H. (2017). A review of reverse logistics and closed-loop supply chains: a journal of clearer production focus. *Journal of Cleaner Production*, *142*, 371–384.

Hirschman, A. O. (1958). The strategy of economic development. *American Journal of Agricultural Economics*, *41*(2), 468–469. Retrieved from `https://doi.org/10.2307/1235188`

Hu, M. C., Fan, C., Huang, T., Wang, C. F., & Chen, Y. H. (2019). Urban metabolic analysis of a food-water-energy system for sustainable resources management. *International journal of environmental research and public health*, *16*(1), 90.

Lin, X. J., & Chang, J. Z. (2004). Analysis of the added value and input-output of taiwan's agriculture and related industries. *Agricultural Economic Series*, *10*(1), 1-24.

Lin, X. J., & Liu, L. (2012). Taiwan's industry linkage effects and measurement of key industries. *Journal of Applied Economics*, *91*, 1-60.

Metzler, L. A. (1951). Taxes and subsidies in leontief's input-output model. *The Quarterly Journal of Economics*, *65*(3), 433-438.

Pagotto, M., & Halog, A. (2016). Towards a circular economy in australian agri-food industry: An application of input-output oriented approaches for analyzing resource efficiency and competitiveness potential. *Journal of Industrial Ecology*, *20*(5), 1176-1186. Retrieved from `https://doi.org/10.1111/jiec.12373`

Rasmussen, P. N. (1956). *Studies in inter-sectoral relations.* E. Harck.

Rizos, V., Behrens, A., van der Gaast, W., Hofman, E., Ioannou, A., Kafyeke, T., & Topi, C. (2016). Implementation of circular economy business models by small and mediumsized enterprises (SMEs): Barriers and enablers. *Sustainability*, *11*.

Schanes, K., Dobernigab, K., & Gözet, B. (2018). Food waste matters - a systematic review of household food waste practices and their policy implications. *Journal of Cleaner Production*, *182*, 978-991.

Schneider, P., & Avellan, T. (2019). Water-energy-food nexus and sustainability. In *Encyclopedia of sustainability in higher education.* Springe.

Statistic Bureau, Taiwan. (2006). *Input-output tables of taiwan.* Retrieved from `https://www.stat.gov.tw/ct.asp?xItem=26194&ctNode=3088&mp=4`

Statistic Bureau, Taiwan. (2011). *Input-output tables of taiwan.* Retrieved from `https://www.stat.gov.tw/ct.asp?xItem=37004&ctNode=3088&mp=4`

Statistic Bureau, Taiwan. (2016). *Input-output tables of taiwan.* Retrieved from `https://www.stat.gov.tw/ct.asp?xItem=44853&ctNode=671`

Toroptsev, E. L., Marakhovskii, A. S., & Duszynski, R. R. (2019). Equilibrium and input-output modeling of economic environment. *Economic Analysis: Theory and Practice*, *18*(4), 663-680.

Wang, H. F., & Hsu, C. F. (2014). Optimal reutilization of the leased products in a closed loop supply chain. In *Logistics operations, supply chain management and sustainability* (p. 302-322). Springer. Retrieved from `https://hdl.handle.net/11296/sanrme1`

Wang, H. F., & Hsu, H. W. (2010). A closed-loop logistic model with a spanning-tree based genetic algorithm. *Computers & Operations Research*, *37*(2), 376-389.

Wicaksono, A., Jeong, G., & Kang, D. (2017). Water, energy, and food nexus: Review of global implementation and simulation model development. *Water Policy*, *19*(3), 440-462.

Windham, M. P. (1995). Robustifying model fitting. *Journal of the Royal Statistical Society*, *57*(3), 599-609.