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A flexible input-output price model for assessment of a nexus perspective to energy, water, food security policymaking

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ABSTRACT

Input-Output models and their extensions offer multiple prospects to explore the energy, water, food inter-linkages – Energy, Water, Food nexus (EWF-n). This paper takes India as a case study to examine a nexus-informed approach to policy making for redressing the EWF security (EWF-s) challenges. First, a Leontief demand-driven EWF-extended Input-Output model is developed. The Leontief's production functions (representing endogenous, fixed technical coefficients) of the developed model are then further modified using flexible functions to capture EWF-related technological and policy interventions. The resulting changes in the model (to include divergent input substitution possibilities) allow evaluation of policy scenarios with nexus or non-nexus considerations towards EWF-s. These scenarios assess outcomes across diverse domains (physical, social, economic, environmental) in short, medium, and long-run over the period 2015-2047. The results show that not only does the EWF nexus-oriented scenario produce major co-benefits demonstrated in terms of the most significant long-term improvement in EWF outcomes but that it also achieves considerably superior economic, social, and environmental outcomes. Synergies and trade-offs across various policy scenarios are also discussed. The insights obtained from the application of this approach, especially cross-sectorial (EWF), cross-domain, and temporal can provide promising takeaways for policymakers to adopt a robust and sustainable strategy for tackling the EWF-s challenges.

Introduction

The Bonn conference [1] made explicit the requirement to consider challenges facing humanity and the planet overall systemically, rather than applying the sectoral or regional approaches traditionally employed. One specific aspect singled out was the consideration of water, energy and food issues in the light of the obvious interrelationships between them across physical, economic, social and environmental domains [2]. Traditionally these resources have been considered largely in isolation from each other, and policies made concerning these resources have been implemented through largely isolated and insulated institutions as well. The result has often been that a policy deemed appropriate for one of these sectors has led to unwelcome impacts on the others [3,4]. The explicit inclusion of energy, water, and food security (EWF-s) concerns in the Sustainable Development Goals (SDGs) (SDG 7; SDG 2; SDG 6) testifies to the increasing recognition of these challenges [5].

Consideration of EWF inter-relationships or nexus (EWF-n) in their assessments has gained rapid impetus over the past decade. Such nexus-based approaches place the nexus of these resources at the centre of any analyses, allowing the inherent trade-offs to be made explicit and dealt with so that proper and holistic policy settings may be defined. Nexus-based approaches have required new or modified frameworks within which such analyses may be carried out. Input-Output models (IO) provide an effective framework for this effort by as they allow a unified representation of EWF flows within the economies [6].

A host of methods have been employed in various studies for examining the EWF nexus. A few methods examine the physical interrelationships between EWF resources involve accounting of input and output flows [7,8], foot-printing [9], supply chain [10], or life cycle analysis [11–13]. Monetary accounting typically involves analysis of benefits and costs associated with EWF strategies [14], or fiscal transactions in the economy in the energy, water, food sectors through specialised methods like Input-Output analysis [15–17] and Social Accounting Matrix [18].

Simulation-based methods, often system-based [19,20], utilise systems analysis to simulate energy, water, food systems and flows to assess the changes in performance of the system (study area) under different 'what if' scenarios [21]. Optimisation-based methods are commonly used in nexus assessments to minimise cost or maximise net economic benefits [22,23]. Other objective functions examined include, for in-

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stance, minimisation of exergy consumption for meeting local EWF demand in Hang *et al.* [24]. Another variation in optimisation-based methods are economic methods based on optimisation principles, like the Computable General Equilibrium (CGE). This method is frequently used in nexus assessments to examine the economy-wide impacts of energy, water, food interventions at national, regional [26], and global levels [27].

Participatory methods are also used for redressing nexus-related issues such as the Delphi method [28,29], interviews, workshops, problem and stakeholder analysis through participatory model-building using causal loop diagrams [30]. Statistical methods, including econometric methods, in the context of nexus, are used to examine EWF interlinkages, factors affecting the nexus, and past trends, and to compare relative EWF efficiencies. Some examples of such methods are regression-based analysis [31,32], dynamic panel modelling [33], and Data Envelopment Analysis [34].

Integrated methods use a combination of methods such as a combination of hydrological (simulation) and economic models (accounting) [35–37]; energy (accounting) and water (simulation) models in Howells *et al.* [38], and accounting (value chain analysis) and participatory models (IAD) in Villamayor-Tomas *et al.* [39]. Indicator-based assessments provide a bridge between non-equivalent dimensions of the nexus, like physical, social, economic and so on [2,40–43]. This is achieved through selection of indicators for specific dimensions of interest, for each resource at different levels and scales.

However, the choice of method for this study focuses particularly on appropriateness of the method in terms of providing policy-useful insights for promoting EWF security at the national level. While CGE models and IO based models are both used for such applications, IO underlying analytics offers significant flexibility in terms of representing the structure and dynamics of an economy at disaggregated levels. It also provides a sound basis to represent market and non-market elements of the economy in a balanced manner, particularly capturing features that are specific to the mixed market/non-market developing economies [44]. Moreover, it is relatively more transparent in terms of both assumptions and computational approach. In view of the above noted advantages of the IO model and keeping in mind the purpose of this research, a EWF-extended IO-based framework is used in this study.

IO models are being used increasingly for understanding EWF economic, environmental, and trade implications [44–47]. Environmentally extended Input-Output models (EEIO), in particular, are more suited for resource accounting and nexus assessments as they bring together economic systems and natural resources, and allow estimation of direct as well as indirect monetary, material, and resource flows (within and outside of economies) in response to economic growth and demand from final consumers [6,15–17],[47–56]].

The existing IO-based EWF assessments focus mostly on the physical EWF interdependencies, predominantly in the form of a snapshot analysis or identification of critical nodes and flows, supply chain analysis, quantifying direct and indirect EWF flows embodied across national and regional economies, and their input-output efficiencies [6,15,16,34,45–48,50–55,58,57,59]. Only a few of such studies extend the IO analysis to include the environmental linkages [17,49,60].

Policy analysis has however remained very limited in such assessments [44,55,59]. Bellezoni et al. developed an economic-ecologic IO framework to assess water, energy and land uses, GHG emissions and employment levels through different ethanol supply scenarios [59]. Sharma et al. assessed the macroeconomic impacts of policies targeted towards energy security improvements, while also especially identifying the trade-offs between energy security and socioeconomic outcomes in seven major Asian economies[43]. Though useful, this study limited its scope to only energy security, thus lacking EWF-n considerations and related environmental implications. Deng et al. utilized a multi-objective optimization model based on multi-regional input–output analysis to balance various policy targets in terms of outcomes like employment, energy consumption, water use, carbon emissions, and pollutant emissions [55]. Though these studies touch upon some socio-economic and environmental elements, their coverage is limited. Insight into many other factors, like EWF adequacy, access, affordability, acceptability, creation of skilled and unskilled employment, import dependencies, impact on GDP, is necessary for a holistic outlook towards ensuring a sustainable approach to EWF security.

This work overcomes this lack of a comprehensive integrated analysis of policies targeted towards EWF securities and their implications, in terms of synergies and trade-offs, on respective and other resource securities, socio-economic and environmental domains. This paper discusses the development of the EWF-extended flexible IO price model, and its application to the policy analysis of EWS-s. The assumption of fixed-coefficients in the price version of Leontief IO model, prevents the real-life simulation of cost-push price effects when relative prices change [61]. Therefore, the flexible IO price model imparts much-needed realism into the analysis by allowing for price-induced input substitution in response to technology or policy interventions using alternative cost structures.

The EWF-s challenge is of particular relevance to India as it confronts the need to support an additional 320 million people by 2050 [62]. The resulting demand for economic growth and increasing per-capita consumption will further exacerbate the stress on the EWF systems, making their equitable, safe and reliable access one of the top policy priorities. Climate change introduces a further complicating factor into the mix, making the EWS-s challenge even more difficult to meet. Attaining an inclusive economic growth for India, therefore, necessitates a critical investigation of interconnections across EWF.

Therefore, this study using India as a case study, demonstrates the application and usefulness of the EWF-extended flexible IO price model. An EWF-extended flexible IO price model is developed for India to empirically investigate the co-benefits or trade-offs between EWF-s, social, economic and environmental outcomes resulting from scenarios underpinned by EWF-s considerations (nexus and non-nexus), to satisfy future (short, medium, and long run) EWF demand in India.

Methodology

The methodological framework (Fig. 1) used in this study consists of three major components: a) *Analytical framework*, b) *Scenario development*, and c) *Scenario Impacts.*

Analytical framework

The core methodology centers around the development and application of an *EWF-extended IO model*. The model developed for this study is a variation of EEIO models used for environmental accounting with a specific focus on understanding EWF requirements of economic systems. The overall analytical framework and the implementation of techno-economic policy changes in the model are briefly shown in Fig. 2.

The base IO table, composed of matrices A-D, is transformed into IO coefficients matrices. Notations used in the procedure are presented in Table 1.

Assuming Leontief fixed-proportion production function, the inputs to a particular intermediate sector can be expressed by the linear relations:

$$z_{ij} = a_{ij} \cdot X_j ; m_{mj} = c_{mj} \cdot X_j \text{ and } v_{vj} = c_{vj} \cdot X_j \tag{1}$$

Similarly, the sources of final demand can be determined as:

$$f_{ik} = b_{ik} \cdot F_k ; m_{mk} = d_{mk} \cdot F_k \text{ and } v_{vk} = d_{vk} \cdot F_k \tag{2}$$

Eqs. (1) and (2) form the basis of determining the baseline scenario in the model. Total final demand for year t ($F_k{}^t$), for each row of the IO table, is guided by assumptions on future macroeconomic conditions, particularly economic growth and sectoral contributions (Table S1.11 in Supplementary file S1). This total final demand is comprised of contributions from domestic production sectors, import sectors, and total

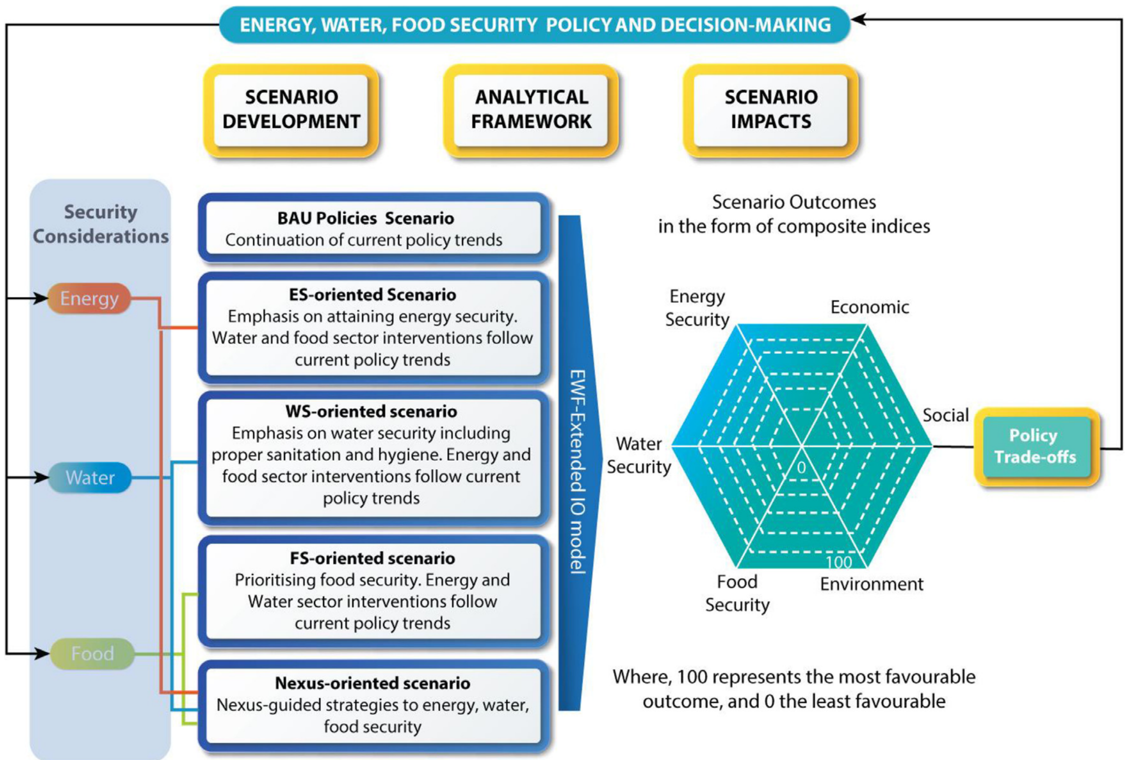

Fig. 1. Methodological framework.

tax paid by final demand sectors, which can be determined from Eqs. (3) and (4).

$$F_i^t = B^s \cdot F_k^{\prime t} \tag{3}$$

$$F_{m+v}^t = D^s \cdot F_k^{\prime t} \tag{4}$$

The outcomes from Eqs. (3) and (4) are then used to estimate total sectoral output, total imports, and total factors of production, including taxes for year t, by using the following IO identity:

$$X_i^t = \left(I - A^s\right)^{-1} \cdot F_i^t \tag{5}$$

Or,

$$M_m^t + V_v^t = \left[C^s \cdot (I - A^s)^{-1} \cdot B^s + D^s\right] \cdot F_k^{\prime t} \tag{6}$$

Finally, the individual components in the IO table (including z_{ij}, m_{mj}, v_{vj}, f_{ik}, m_{mk} and v_{vk}) are estimated using the linear relationship as in Eq. (7).

$$z_{ij}^t = a_{ij}^s \cdot X_j^t \tag{7}$$

Where, $X_j = X'_i$.

In addition to the economic account, other accounts (such as, energy, emissions, and employment) are also developed corresponding to the sectoral classification (Table S1.8 (a-h) in Supplementary file S1). The sectoral energy requirement for year't' can be estimated by:

$$E_{fi}^t = e_{fi}^s \left(I - A^s\right)^{-1} \cdot F_i^t \tag{8}$$

The next steps demonstrate how the IO model used in this study evaluates the impacts of shocks or changes in technology for designing future technology scenarios. To implement this, the IO coefficients are exogenously changed. IO coefficients describe physical intensities of inputs used in a production process, both in terms of intermediate and primary factor inputs, when the physical unit of inputs can be redefined as the quantity of output of that particular sector, which can be bought for a dollar at base year prices [63].

A change in technology will induce changes in the input-mix of various production sectors. Resultantly, the prices of sectoral outputs would change. This type of sectoral price effects from technological change is estimated using the Leontief's IO price model. The changes in sectoral prices are determined from Eq. (9) as:

$$P_i = \left[I - A'\right]^{-1} . C'_j \tag{9}$$

This translates the base IO value data into price and quantity data, by normalizing the initial (base) prices in the model to unity. Next, the new sectoral prices in year t are determined based on new technical coefficients, which were updated exogenously in the previous stage, as shown in Eq. (10).

$$P^t = \left[I - A'^t\right]^{-1} . C'^t \tag{10}$$

This would give the index of changes in sectoral prices, compared to the base year. The changes in sectoral prices (in the previous stage) will induce substitution among factor inputs. The standard IO model however assumes perfect complementarity between factor inputs through the use of Leontief fixed-proportion production function, thus ignoring substitution possibilities. These substitution possibilities are considered in this study by introducing flexible neo-classical production functions in the standard IO model. The behavioural model (in Fig. 2) refers to these price-responsive substitution possibilities in this study.

A Leontief production function, with zero elasticity of substitution, represents final output as:

$$X_j = \min\left[\frac{h_{ij}}{\alpha_{ij}}, \frac{v_{vj}}{c_{vj}}\right] \tag{11}$$

Since the elasticity of substitution in this function is zero, changes in price will not have any effect on the choice of inputs used. Thus, the amount of intermediate inputs can be determined from the formula that is similar to Eq. (7), i.e.,

$$h_{ij} = \alpha_{ij} \cdot X_j$$
$$v_{vj} = c_{vj} \cdot X_j \tag{12}$$

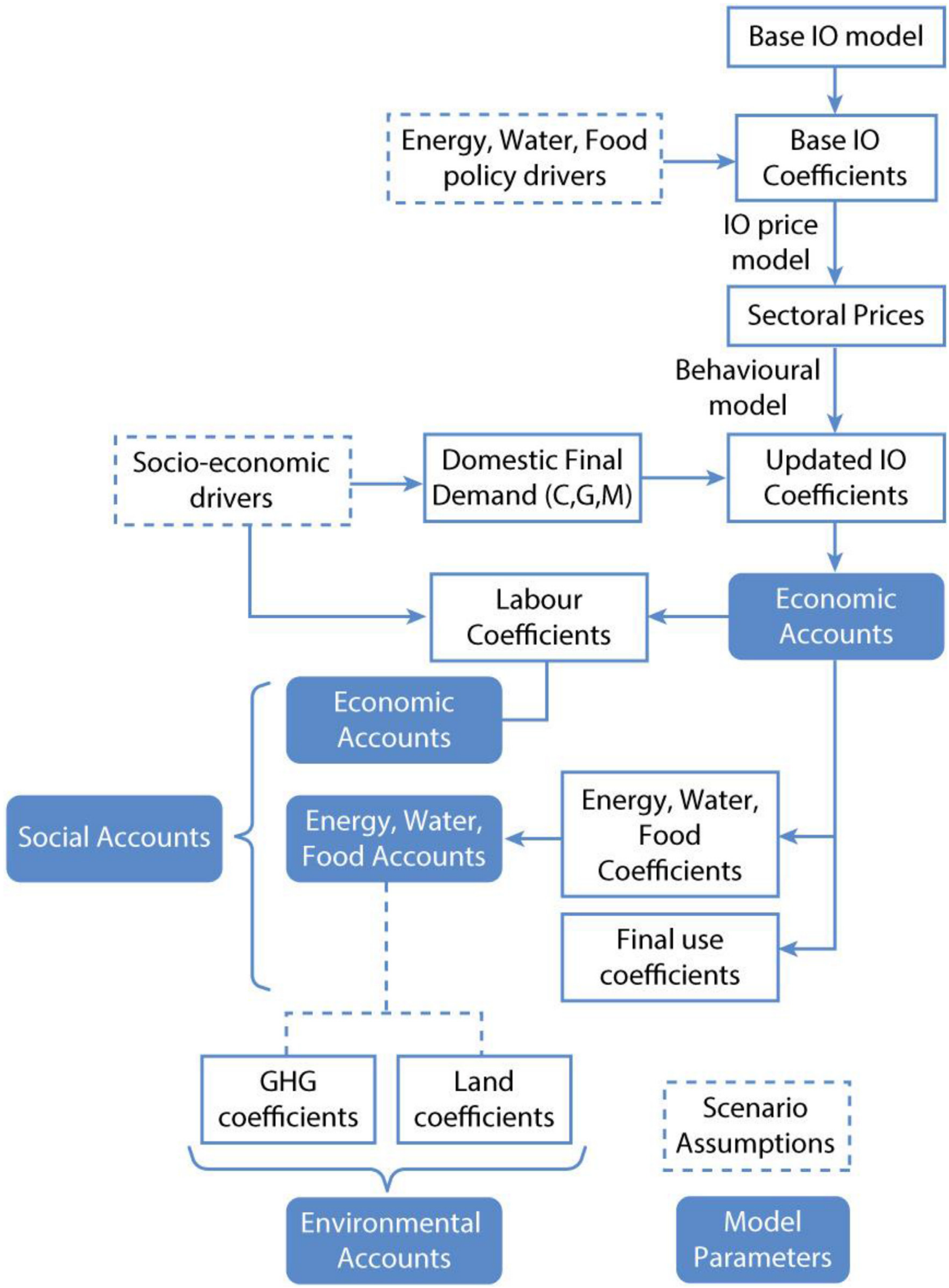

Fig. 2. Analytical framework.

However, substitution possibilities, say in the case of intermediate inputs supplied either by domestically produced or importable inputs, are represented through a Constant Elasticity of Substitution (CES) production nest as:

$$h_j = \left[a_{ij} \cdot z_{ij}^{\frac{\sigma-1}{\sigma}} + c_{mj} \cdot m_{mj}^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}} \tag{13}$$

Eq. (13) can also be shown as an input demand function:

$$\begin{aligned} z_{ij} &= 1^{\sigma-1} \cdot a_{ij} \cdot \left(\frac{p_j}{p_{ij}} \right)^{\sigma} \cdot h_j \\ m_{mj} &= 1^{\sigma-1} \cdot c_{mj} \cdot \left(\frac{p_j}{p_{mj}} \right)^{\sigma} \cdot h_j \end{aligned} \tag{14}$$

Using Eq (14), instead of Eq. (13), thus allows us to capture demand behaviour through substitution possibilities within the IO framework.

Table 1
Nomenclature for the analytical framework.

a_{ij}	Technical coefficients
α	Coefficients for intermediate inputs, comprising of a_{ij} and c_{mj}
A^t	Matrix of input–output technical coefficients, adjusted for new energy technology
A^s,B^s,C^s,D^s	Coefficients matrices for base year‘s’.
b_{ik}	Final use coefficients
C^t	Matrix of primary factor (and import) coefficients for year t
c_{mj}	Import coefficients
c_{vj}	Primary factors coefficients
C_j	Sum of factors of production and imports for each sector j
$d_{mk,}$ d_{vk}	Import coefficients,
E_{fi}	Energy of type *f* consumed by production sector *i*
e_{fi}	Energy intensity of sector *i*
e	Matrix of energy intensities
E	Matrix of total energy use
$e.[I-A]^{-1}$	Sectoral energy intensities for the baseline scenario
F_k	Total final demand k
$F_k{}^t$	Total final demand for year t
$F'^t{}_k$	Transpose of total final demand for year t
$F_i{}^t$	Total final demand comprising contribution from domestic production sectors
$F_m{}^t$	Total final demand comprising contribution from import sectors
$F_v{}^t$	Total tax paid by final demand sectors
f_{ik}	Output of sector i used by final demand k
h	Intermediate inputs, comprising inputs from z_{ij} and m_{mj}
h_j	Total intermediate inputs used in sector j
h_{ij}	Intermediate inputs from sector i to sector j
M_m	Total imports for year t
m_{mj}	Import from foreign sector ‘m’ used by domestic sector ‘j’
m_{mk}	Import from foreign sector m used by final demand k
σ	Elasticity of substitution
P^t	Vector of new sectoral price levels
p_j	Unit costs of total intermediate inputs used in sector j
p_{ij}	Unit costs of domestically produced intermediate inputs i used in sector j
P_{mj}	Unit costs of importable intermediate inputs m used in sector j
v_{vj}	Factor ‘v’ used by sector ‘j’
v_{vk}	Factor v paid by final demand k
$V_v{}^t$	Total factors of production, including taxes for year t
X_j	Total output of sector ‘j’
$X_i{}^t$	Total sectoral output of sector *i* for year t
$X_j{}^t$	Total output of of sector *j* for year t
z_{ij}	Output of sector ‘i’ used by sector ‘j’,
z_{ij}	Intermediate inputs from domestic sector

For nesting structures of different sectors used in this study, refer to Fig. 1.2 (a-e) in Supplementary file S1.

The new IO structure (as developed using Eqs. (12) and (14)) forms the basis to calculate the updated economic accounts. The results (such as GDP and sectoral output) are then compared with those developed in the first stage for the baseline scenario, using Eq. (7). The difference thus shows an economic impact of technological change. Further, the updated IO table is used as a basis to develop other accounts. Again, the difference between these results and those estimated in the baseline scenario shows impacts on energy, water, food, land, emissions, and employment.

Scenario development

To better understand the effectiveness of a nexus-informed approach against the existing or non-nexus guided approaches to EWF-s policies in India amongst the various options available to policy makers, five basic scenarios are considered (Table 2). The BAU scenario assumes a continuation of current trends, policies, and planned investments in each of the EWF sectors. The *ES Scenario* envisages a sustainable energy supply in the country ensured largely by improving energy self-sufficiency and rigorous promotion of energy efficiency measures. The *WS Scenario* foresees improved water supply and higher levels of wastewater (ww) treatment. This includes ensuring proper sanitation to counter the negative effects of poor hygiene on water security. On the demand side, the *FS Scenario* seeks to eradicate undernourishment and malnutrition by educating the masses about diet diversification and by improving access to food. On the supply side, it envisages higher yields, a higher increase in area under irrigation, reduced seed and wastage rates, improved feed conversion ratios, higher use of chemical fertilisers, and better soil nutrient management. The other sectors in non-nexus scenarios (ES, WS, and FS scenarios) are assumed to follow similar trends as the BAU scenario. In the *Nexus Scenario*, the choice of strategies and solutions to attain EWF-s is nexus-guided, i.e., those which do not incur trade-offs with other resource sectors in the EWF-n. **Fig. 3** shows more details wherein identical color intensities across individual rows represent similar levels of interventions. For more details, refer to Table S1.13 in Supplementary file S1.

Scenario impacts

The examination of impacts of various policy scenarios is carried out in terms of impact attributes and composite indices, reflecting EWF securities, social, economic, and environmental outcomes. The impact attributes have been chosen in this research to reflect the EWF security aspirations of India and relevant social, economic, and environmental outcomes. While some of the chosen attributes are widely used in the literature on EWF-s assessments, others have been designed specifically for this research – to capture specific social, institutional, and environmental domains relevant to the EWF nexus in the Indian context. Supplementary file S1 (Table S1.14) provides further details on the impact attributes chosen for this study.

Per capita calorie consumption, as a food security impact attribute, has also been assumed to be covered under dietary diversity based on the reasoning that dietary diversification only begins to occur after fulfillment of dietary calorie needs [64].

Table 2
Sectorial classification (n=93) for IO model used in the study.

Energy sectors (34)	Food Sectors (24)	Water Sectors (12)	Factors of Production (5)
Energy resource extraction	*Paddy*		
Coal mining	*Wheat*	*Water pumping – diesel-based*	Skilled labour
Crude oil exploration	*Jowar*	*Water pumping – electricity based*	Unskilled labour
Natural gas production	*Bajra*	*Water pumping – solar-based*	Capital
Other mining	*Maize*	*Conventional irrigation*	Land
	Other grains	*Efficient irrigation*	Natural resources[1]
Non-electric	*Roots and tubers*	*Highly efficient irrigation*	
energy supply	*Other vegetables*	*Municipal and industrial water*	**Final Demand (6)**
Petroleum refining	*Fruits*	*supply/treatment*	Private
LPG	*Pulses*	*Sea water desalination*	Consumption (rural)
Kerosene	*Oilseeds*	*Centralised ASP*	Private
Petrol	*Sugarcane*	*Decentralised WSP*	consumption (urban)
Diesel	*Sugarbeet*	*Decentralised MBR*	Government
Naphtha	*Other crops*	*Treated sewage water*	Expenditure
Fuel oil	*Other animal products*		Investment
Other petroleum products and coke	*Milk*	**Other sectors (23)**	Exports
Gas distribution	*Cattle meat*	*Cotton*	Imports
	Other meat	*Jute*	
Electricity supply	*Vegetable oil*	*Cattle*	
Electricity T &D	*Milk products*	*Wool*	
Coal sub-critical	*Processed rice*	*Forestry*	
Coal super-critical	*Sugar*	*Fishing*	
Coal ultra-supercritical	*Fish*	***Industry (12)***	
Coal IGCC	*Other preserved food*	*Nitrogen fertilisers*	
Coal pre-CCS		*Phosphorus fertilisers*	
Coal post-CCS		*Potassium fertilisers*	
Gas power plants		*Chlor-alkali*	
Gas CCS		*Textiles*	
Nuclear PWHR		*Paper*	
Nuclear LWR		*Nonmetal*	
Nuclear FBR		*Iron and steel*	
Large hydro		*Non-ferrous*	
Small hydro		Other manufacturing	
Wind onshore		Other chemical and Petrochemicals	
Wind offshore		Construction	
Oil power		***Services (1)***	
Biomass to electricity		**Transport (4)**	
Waste to electricity		Road transport	
Solar PV		Rail transport	
Solar CSP		Air transport	
Solar distributed		Water transport	

Abbreviations: LPG: Liquefied Petroleum Gas, T&D: Transmission and Distribution, IGCC: Integrated Gasification Combined Cycle, CCS: Carbon Capture and Storage, PWHR: Pressurised Heavy Water Reactor, LWR: Light Water Reactor, FBR: Fast Breeder Reactor, ASP: Activated Sludge Process, WSP: Waste Stabilisation Ponds, MBR: Membrane bio-reactors

[1] Non-producible natural resource inputs like Coal, oil, natural gas, minerals, fisheries and forestry (Hertel et al. 2016)

Fig. 3. Scenario storylines.

The analytical framework estimates the value of each impact attribute for each time frame of the model. The absolute values of attributes obtained in different scenarios over time are normalized and then scaled from 0-100, where 100 represents the most favorable outcome, and zero, least favorable. The attributes for which a higher value indicates a more favorable outcome (for example, food diversity, access to modern energy sources) and those with high values indicating unfavorable outcomes (for example, energy/food import dependencies, water stress) are normalized accordingly as shown in Eqs. (15) and (16).

$$x = [x - \mathrm{Min}(x)]/[\mathrm{Max}(x) - \mathrm{Min}(x)] \quad (15)$$

$$x = [x - \mathrm{Max}(x)]/[\mathrm{Max}(x) - \mathrm{Min}(x)] \quad (16)$$

Composite indices are developed from a set of context-relevant impact attributes to indicate the overall outcome of a particular security dimension. For example, a composite energy security index is calculated as the mean of energy security attributes. The formulation of composite indices allows an inter-scenario comparison of security outcomes and the level of co-benefits and trade-offs between these outcomes.

Further, to quantify the performance of the alternative policy scenarios against the BAU scenario, a scoring index is created. This index assigns points to each of the attribute in a range of (-5) to (+5) corresponding to outcomes ranging from very high (90-100%), high (50-90%), moderate(25-50%), low(10-25%) and slight (0-10%) negative and positive impacts compared to the BAU scenario outcomes respectively. Correspondingly, the improvement or deterioration relative to the BAU scenario is ascertained in percentage terms.

Data and parameters

The base year (2015) IO is obtained by rebasing the 2011-12 IO table for India available from GTAP [65], which is more recent than the Indian national account statistics. The latest data available at the time of the study was from GTAP for year 2011-12, which was first rebased to 2015-16 not just with economic structure as well as technological mix across energy, water, food sectors. First, the economic structure was rebased using the macroeconomic parameters obtained from official data on macroeconomic indicators such as final consumption expenditure, government expenditure, investment, and exports for the Indian economy for the year 2015-16 [66]. Later, fuel and technological data across energy, water, food sectors such as the electricity generation fuel-mix, and agricultural production, for the same year was used as a basis for IO disaggregation. It was assumed that the technological structures in other sectors underwent no significant change during 2011 and 2015. Finally, to ensure that the disaggregated IO is not only a balanced data set but it represents the current macroeconomic situation of the economy for the year being estimated, a comparison of GDP so obtained after rebasing with the actual GDP of 2015-16 was made, which resulted into a minor difference of 6 percent.

The original GTAP India data with 68 sectors is disaggregated into 93 sectors (Table 2), of which 34 are energy sectors, 24 food sectors, and 12 water sectors, to suit the purpose and focus of this study. The disaggregation of sectors also addresses the commonly cited problem of aggregation bias in IO analysis [67] Piñero et al. 2015. The method used for disaggregation is briefly explained in Table S1.12 in Supplementary file S1.The period of analysis in this study is 2015-2047. The modeling time frames are in accord with the five-year planning system of India. Model time frame years chosen to represent short, medium, and long-term are 2022 (end of the 13th five-year plan), 2032 (end of the 15th five-year plan), and 2047 (end of the 18th five-year plan) respectively.

The IESS 2047 model developed by NITI Aayog [68] is used as a platform for generating energy sector scenarios. Socio-economic, environmental, water, and food parameters have been aligned with IESS additionally. Several reports, publications, and databases have contributed to reflect the growth of the economy and sectoral shares along with some other assumptions [69–72]. Table 3 summarizes key data sources for IO disaggregation; EWF, social, and environmental accounts; and elasticities of substitution. For further details on Table 3 and assumptions about population and economic growth drivers refer to Table S1.11 in Supplementary file S1.

Table 3
Details of assumptions and key data sources.

Purpose		Key Sources
Growth drivers	GDP	[69–71]
	Population	[72]
IO Disaggregation	Energy	[68,73,74]
	Water	[75,68]
	Food	[76–79]
EWF, material, social, and environmental accounts	Energy	[76,80–82]
	Water	[83–87]
	Food	[78,88,89]
	Employment	[76,90–94]
	Emissions	[68,95,96]
	Land	[68,74,97–101]]
	Fertilizers	[102]
Elasticities of Substitution		[103–111]

Results and discussion

Section 3.1 reports the overall findings pertaining to trade-offs and co-benefits observed between EWF-s, social, economic, and environmental composite indices for various scenarios. Section 3.2 presents a deeper analysis and reasoning behind such findings, keeping the BAU scenario as a baseline for comparison. Section 3.3 suggests policy implications and recommendations from the analysis of EWF-s, social, economic, and environmental outcomes of various policy scenarios

Trade-offs and co-benefits between composite indices

Fig. 4 (a-c) shows increasingly pronounced trade-offs from the short-to-long term. The worst outcomes for *energy security, water security and food security* are consistently generated in the FS, ES and BAU scenarios respectively over the study period. The most favorable outcomes for *energy security* in the short and medium-term are seen in the Nexus scenario and in the ES scenario in the long term. The FS scenario produced the most favorable *water security* outcomes in the short term, while the Nexus scenario produced the most favorable outcomes in the medium and long term. The Nexus scenario consistently generated the most favorable outcomes for *food security* over the entire modeling period.

The WS and ES scenarios produced the least and most favorable *economic* outcomes respectively in the short, medium, and long term. The worst *social* outcomes were generated in the BAU scenario in the short term, and in the ES scenario in the medium and long term. The Nexus scenario produced the best social outcomes in all periods. The Nexus scenario also produced the most favorable *environmental* outcomes across all periods. The least favorable environmental outcomes in the short and medium-term were generated in the ES scenario while the worst environmental outcomes in the long term were generated in the BAU scenario.

Analysis of outcomes – alternative policy scenarios versus BAU scenario

The key findings for alternative scenarios in terms of percentage deviations from BAU (Table 4) are:

3.2.1 Nexus scenario yields the highest number of notable improvements (more than 50 %) compared to the BAU scenario, all in long term and for the following attributes: coal import dependency, relative water stress, per capita freshwater withdrawals,

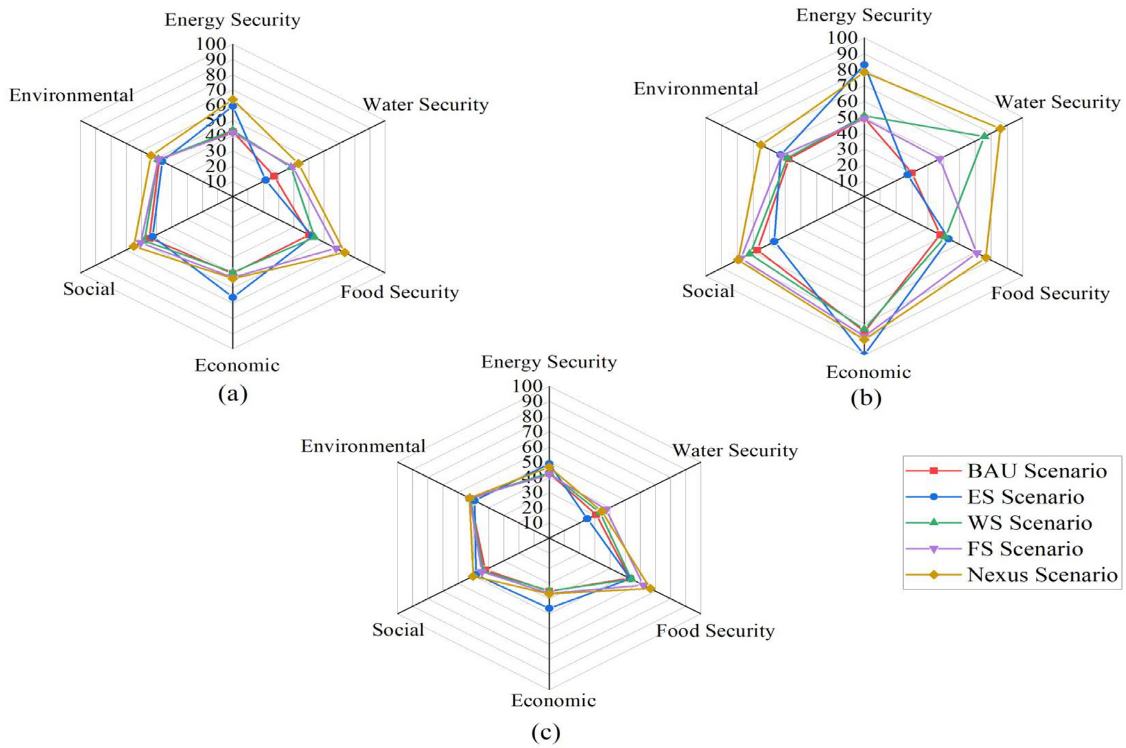

Fig. 4. Short (a), Medium (b), and long (c) term socio-economic, environmental, and EWF security outcomes.

Table 4
EWF-s, Socio-Economic (So-Ec) and Environmental (Env) outcomes for alternative policy scenarios, in comparison with the BAU scenario.

ATTRIBUTES		Short term Scenario outcomes				Medium term Scenario outcomes				Long term Scenario outcomes			
		ES	WS	FS	NEXUS	ES	WS	FS	NEXUS	ES	WS	FS	NEXUS
ES	ENERGY INTENSITY												
	PER CAPITA ENERGY CONSUMPTION												
	COAL IMPORT DEPENDENCY												
	OIL IMPORT DEPENDENCY												
	GAS IMPORT DEPENDENCY												
	ELECTRICITY GENERATION: FUEL DIVERSITY INDEX												
	VALUE OF NET ENERGY IMPORTS OF TOTAL NET IMPORTS												
	ACCESS TO MODERN COOKING FUELS												
WS	RELATIVE WATER STRESS												
	WATER PRODUCTIVITY												
	PER CAPITA FRESHWATER WITHDRAWALS												
FS	FOOD ACCESSIBILITY												
	FOOD NET IMPORTS AS % OF TOTAL NET IMPORTS												
	RURAL FOOD DIVERSITY												
	URBAN FOOD DIVERSITY												
EC	PER CAPITA GDP												
	TRADE BALANCE / GDP												
	INFRASTRUCTURE INVESTMENTS / GDP												
SO	EMPLOYMENT												
	RURAL FOOD AFFORDABILITY												
	URBAN FOOD AFFORDABILITY												
	RURAL ENERGY AFFORDABILITY												
	URBAN ENERGY AFFORDABILITY												
	ACCEPTABILITY												
	HEALTH												
	SKILLED EMPLOYMENT												
ENV	PER CAPITA CARBON EMISSIONS												
	CARBON EMISSIONS PER UNIT ECONOMIC OUTPUT												
	PER CAPITA LAND REQUIREMENT												
	FERTILISER NUTRIENT APPLICATION DIVERSITY												
	FERTILIZER USE PER UNIT OF CROP OUTPUT												
	PER CAPITA FUGITIVE EMISSIONS												
	FUGITIVE EMISSIONS PER UNIT ECONOMIC OUTPUT												

Very High Negative Impact	High Negative Impact	Moderate Negative Impact	Low Negative Impact	Slight Negative Impact	No Impact	Slight Positive Impact	Low Positive Impact	Moderate Positive Impact	High Positive Impact	Very High Positive Impact

and rural and urban food diversity. The most notable improvement of all is for per capita freshwater withdrawals. The reasoning behind these findings is discussed in forthcoming paragraphs.

The additional reduction in demand for imported coal in the Nexus scenario, in comparison with the ES scenario, is caused by higher reduction in electricity demand in this scenario arising from greater energy efficiency improvements at various stages of crop production, water efficiency improvements, particularly for irrigation, and choice of less energy-intensive technologies for wastewater treatment. The reduced electricity demand results in reduced coal consumption and therefore fewer coal imports. The Nexus scenario produces better food security-related outcomes than the FS scenario as a result of its better food diversity compared to the FS scenario; this likely results from the resulting higher incomes in the Nexus scenario.

The Nexus scenario shows the highest improvement in water security outcomes, such as relative water stress, per capita freshwater withdrawals, compared to the BAU scenario in the medium and long term – even better than the WS scenario where water security is the prime focus. Such outcomes result from simultaneous introduction of less water-intensive renewables, like distributed solar, a transition towards less water-intensive diets, and improvements in water efficiencies across different sectors in this scenario. The Nexus scenario seems to produce better food security-related outcomes than the FS scenario as a result of its better food diversity; owing, possibly to, higher incomes (economic output per capita) in the Nexus scenario.

3.2.1 Only the ES scenario shows some notable improvement (more than 50 %) in the short and long term; however, the most notable long-term improvement in this scenario is limited to energy security attributes only, i.e., reduction in energy imports expenditure. Likewise, long-term notable improvements in the FS and WS scenarios are limited to water and food security attributes respectively.

3.2.2 It is noticed that GDP estimates do not exhibit considerable difference despite scenario assumptions, like reduction in energy import dependence in ES and Nexus scenarios. While this assumption, for instance, in the ES scenario reduces the energy and net energy imports by 14 % and 35 % respectively relative to BAU scenario, this reduction in total imports makes it much less prominent as imports also arise significantly from non-energy industries (particularly manufacturing, non-ferrous metals, chemicals, and petrochemicals) and services sectors. As a result, total imports in the ES scenario turn out to be only 4 % less than the BAU scenario. Initiatives, like Make-in-India, to boost the country's manufacturing sector could affect these estimates, which however is not in the current scope of this study.

3.2.3 Similarly, although total employment opportunities do not differ much from one scenario to another, there are considerable inter-sectorial contrasts; for example, by the long term, the FS scenario is expected to generate 15 million more jobs in the agriculture sector than the BAU scenario. Likewise, the ES scenario will generate around 270 thousand more jobs in the energy sector than the BAU scenario would generate. Around 43 thousand additional jobs will be created in the water sector in the WS scenario compared to the BAU scenario. The Nexus scenario shows a considerable rise in EWF sector jobs compared to the BAU scenario and is also the second-highest in terms of the number of jobs created in all the scenarios in the long term.

Next, are some findings obtained using the scoring criteria for these scenarios (Fig. 5 (a-f)

3.2.1 The ES and Nexus scenarios show marked improvement in energy security over the BAU scenario wherein the ES scenario leads the Nexus scenario in the short and long term while in the medium term, improvements in the Nexus scenario, compared to the BAU scenario, surpass those in the ES scenario with better fuel diversity in electricity generation and lower coal import dependency, although the value of net energy imports of total net imports is still lowest in the ES scenario. In the long term, the ES scenario again shows the highest improvement over the BAU scenario with most favorable gains observed for energy intensity, oil import dependency, and value of net energy imports of total net imports, while coal import dependency is still lowest in the Nexus scenario. Although the Nexus scenario also assumes high domestic oil production, it still lags in oil import dependency improvements as compared to the ES scenario due to its low focus on biofuel production.

3.2.2 The Nexus scenario, driven by concurrent considerations for EWF-s, shows the highest improvement in water security compared to the BAU scenario in the medium and long term, largely owing to a distinct improvement in per capita freshwater withdrawals and relative water stress outcomes – even better than the WS scenario. The FS scenario shows high improvement compared to BAU scenario in the short term with its assumption about shifting of dietary focus from water-intensive grain crops to less water-intensive non-grain crops and low biofuel penetration in the energy mix. The ES scenario shows worse outcomes compared to the BAU scenario, in short, medium, and long term with a high share of centralized water-intensive modes of energy generation; water security improves in this scenario in the long term but remains lower than that in the BAU scenario. The improvement in water security in the long term takes place on account of better water productivity of the economy, mainly attributed to generation of high economic output in the scenario.

3.2.3 In the short term, food security attains equal highest level of improvement in the FS and Nexus scenarios; in the medium and long term, the Nexus scenario scores the highest level of food security. The WS scenario shows an almost equal level of food security as in the BAU scenario across all periods.

3.2.4 The economic outcomes in all alternative scenarios are higher than the BAU scenario across all periods. The ES scenario consistently produces the best economic outcomes compared to the BAU scenario with prominently positive outcomes for trade balance with a reduction in energy imports and high investments in energy infrastructure needed in this scenario. The improvement remained high and steady during the entire modeling period, slightly higher in the medium and long term.

3.2.5 The social outcomes in the ES and Nexus scenario show the highest equal improvement over those of the BAU scenario in the short term primarily owing to high improvement in urban energy affordability but declining sharply for the ES scenario over the medium and long term primarily due to decline in rural energy affordability and acceptability levels. In the medium term, the Nexus scenario produces the best social outcomes with superior health outcomes (pertaining to clean air, improved water sources and sanitation facilities, and diversified diet), urban energy affordability, and rural and urban food affordability. The FS scenario shows the greatest improvement in the long term, followed by the Nexus scenario. The Nexus scenario lags largely due to the decline in rural energy affordability. This is due to an assumed high rate of transition from low-priced biomass to high-priced energy cooking fuels, resulting in increases in rural energy expenditure.

3.2.6 In the short term, environmental outcomes of the ES and Nexus scenario are marginally worse than the BAU scenario with a high land requirement from the ES scenario and high energy-related fugitive emissions in both scenarios from increased domestic energy production. In the medium term, the Nexus scenario shows the best outcomes for the environment relative to the BAU sce-

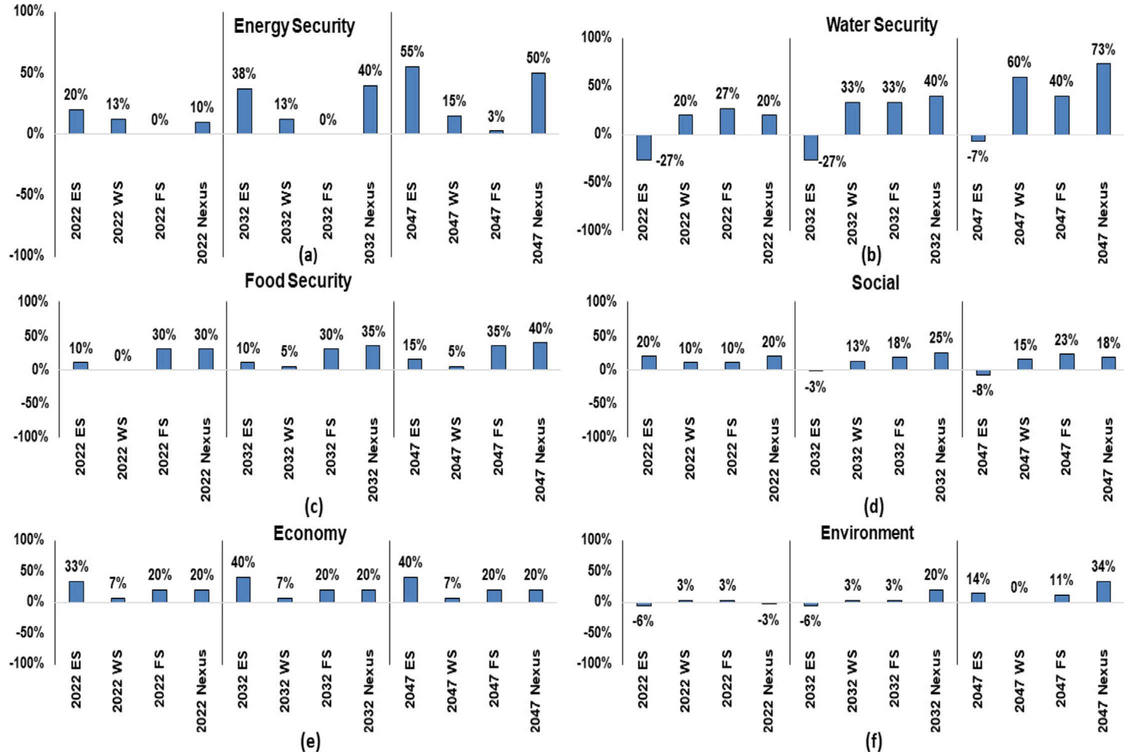

Fig. 5. (a-f): Resulting percentage deviations of scores for various security outcomes in comparison to the BAU scenario, in short, medium, and long term.

nario with considerable improvement over the BAU for each environmental attribute except land requirement. In the long term, the Nexus scenario stands out with a high improvement in per capita carbon emissions and fertilizer application diversity index, the land requirement however remaining higher than the BAU levels.

On an aggregated level, a comparison of alternative scenarios with the BAU scenario depicts all scenarios to be better than the BAU scenario (Fig. 6 (a-b)) in all periods, with maximum improvement observed in the Nexus scenario in case of aggregated EWF-s outcomes (52%). Collectively (also including socio-economic and environmental outcomes), the Nexus scenario achieves 13, 28, and 37 % improvement over the BAU scenario in the short, medium, and long term respectively. The minimum improvement is observed in the WS scenario – 5, 9, and 13 % in the short, medium, and long term respectively.

Policy implications and recommendations

The analysis of EWF-s, social, economic, and environmental outcomes of various policy scenarios demonstrated increasingly pronounced trade-offs from short-to-long term suggesting that any trade-offs or co-benefits between the current policies scenario (BAU) and alternative scenarios would be more prominent in the long term. While a short-term analysis may not find the problem to be so challenging, in the long term, these challenges will become much greater in impact, thus indicating a need for immediate action. Similarly, the trade-offs or co-benefits would also be realized more effectively in the long term.

Overall, the current policy scenario seems to be the least favorable of all scenarios, particularly for water security and environmental outcomes. Sustainably attaining EWF-s would, therefore, require additional efforts beyond the current plans.

The analysis of alternative policy scenarios towards EWF-s results into *three major findings*:

3.3.1 Water security and food security outcomes in the Nexus scenario suggest being most favorable, even higher than in the respective sectorial security scenarios, across all periods. Energy security improvements in the Nexus scenario are indicated to be substantial but lower than in the ES scenario. (Refer to Section 3.2. for more details). This finding reinforces the benefits of a nexus approach to EWF-s policy making.

3.3.2 Nexus scenario economic outcomes may not be the most superior ones for India but are nevertheless substantial. The economic outcomes in the Nexus scenario are better than in the BAU scenario but lower than in the ES scenario with the highest improvement in economic outcomes (Refer Section 3.2. for more details). Economic growth is indeed an important policy priority for India. However, the Nexus scenario is likely to achieve a similar level of economic growth (GDP) as the current policies or BAU scenario, with the simultaneous advantage that it is very likely to effectively redress the EWF-s challenge.

3.3.3 Social and environmental outcomes in the Nexus scenario are expected to provide more significant benefits than in any other scenario (Refer Section 3.2. for more details). The Nexus scenario leads to considerably improved EWF-s, social, and environmental outcomes. The improvement in economic outcomes, however, is rather modest in this scenario. Overall, the Nexus scenario seems to be the most desirable for improving EWF-s outcomes in India, while at the same time providing superior socio-economic and environmental outcomes; thus making it the best option from a sustainable development perspective.

Therefore, the key policy recommendation, emerging from this study, is that an integrated approach is essential to effectively tackle the EWF-s issues in India. The successful implementation of the Nexus scenario is, however, contingent upon a few aspects, like the development of commercially viable alternatives, effective land management, horticulture development, and redressal of institutional barriers. Specific-planning during the country's roadmap development phase can help in overcoming these barriers.

The key options indicated by the Nexus scenario would require some sectorial interventions, like significant transformations in the electricity

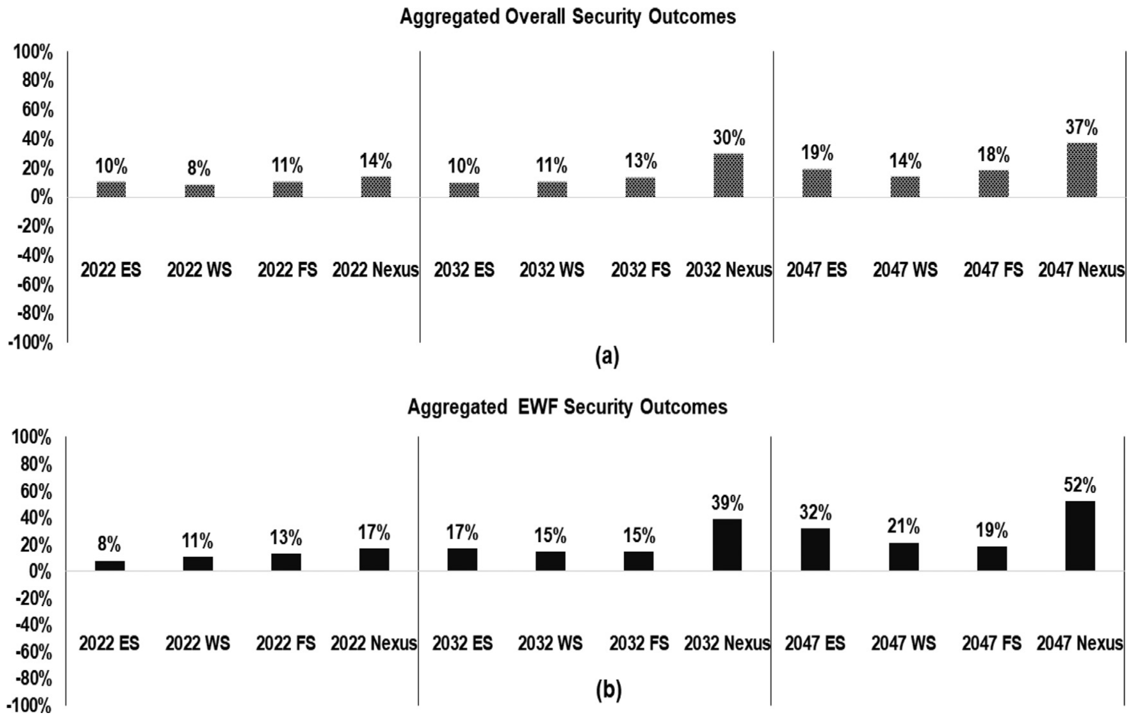

Fig. 6. (a-b): Aggregated EWF and Collective security outcomes for various scenarios w.r.t. BAU scenario.

sector, including increased uptake of renewable energy (RE) technologies like wind, small hydro, and waste-to-energy. The successful integration of highly decentralized and distributed RE technologies would require focus on cost-effectiveness of the interventions (including energy storage technologies), feedstock availability (for waste and biomass-based electricity generation), and infrastructure availability. Successful practical implementation of the Nexus scenario is also subject to higher uptake of micro-irrigation technologies, often challenged by high capital costs [112].

Furthermore, the Nexus scenario is land-intensive due to the type of technologies it assumes, including RE and less energy-intensive decentralized wastewater treatment options. Land constraints can potentially limit the practical and successful implementation of the Nexus scenario. Overcoming institutional constraints and behavioral / cultural barriers, for instance, shifting to a less grain-dominated diet or electric cooking & elimination of the secondary market, is also imperative to the scenario's practicability. Emphasis on research and development in horticulture - to ensure food diversity and nutritional security – is also critical to the practical implementation and securing of benefits foreseen in this scenario [113].

Limitations and future directions

The model developed in this paper addresses the most commonly cited drawbacks of traditional IO models; aggregation bias and fixed input structure assumption [67,114]. Notwithstanding the high degree of criticism that the IO model has faced in terms of its functional abilities, most of the criticism have been discredited as misconceptions surrounding the model [115]. For instance, the IO use of fixed coefficients has been highly criticised due to the underlying assumption about the fixed proportionality of IO coefficients. However, in reality, these coefficients undergo frequent changes due to, for example, innovation, changes in consumer and producer preferences, or policy adjustments [116]. These changes trigger technological changes which further alter factor inputs.

The fixed proportionality of inputs, however, is valid for only the most basic version of IO. In its most traditional form, IO employs the standard Leontief production function formulation where it is usually assumed that the IO ratios remain fixed in physical terms when relative input prices change. However, the traditional IO model can be extended to more general production systems; the Translog production function and the Constant Elasticity of Substitution (CES) production function, for example, are compatible with all possible values for elasticity of substitution for analysing structural change and correspondingly price-induced input substitution ([117–119]. This flexibility makes the analysis more realistic. Other limitation of IO mentioned in the literature are the neglect of prices which can be overcome by price multiplier analysis, which allows the cost-push inflation of exogenous changes in input cost to be determined [114].

In addition to the price-induced change in IO coefficients, another source of change in these coefficients is through scenario assumption. The IO coefficients in this study are altered in accordance to the future fuel mix determined by technical studies, such as the IESS 2047 [68] projections for energy sector. For example, the influence of different levels of penetration of new technologies such as the electric vehicles – as assumed in the technical studies projecting energy demand and supply mix - is reflected in terms of rising electricity demand and correspondingly increased installed capacity of electricity generation. While technological evolution is a dynamic process, the larger aim of this study is to provide a framework for any future study concerning economy-wide implications of energy, water, food security policies and interventions in India.

However, a theoretical shortcoming of the open-economy model used in this study was its inability to take into account the impact of imported commodities' prices on imported and domestic demand, and the impact of these prices on final demand level and structure, implying a constant price assumption for global goods and services – an advantage offered in a closed IO model [120]. It is therefore recommended to assess the changes in household expenditure resulting from changes in household income, caused by direct and indirect effects in an economy, using a closed IO model [25]. Despite limitations, the IO model used in this study offers a robust platform of integrating the social, economic and environmental domains; a prerequisite for meeting the goal of a sustainable development [121].

This study relied primarily on publicly-available secondary information sources including those archived by various national, international, and sectorial planning and developmental agencies. The data so obtained also required additional treatment requiring assumptions wherever necessary. A centralized and updated data and statistic repository could fast-track such studies. Additionally, such a data bank would help guide the data requirements for future nexus studies, more likely to become prevalent over time. The development of Input-Output tables is an exhaustive process. As a result, the IO tables are published after long time intervals. Updating IO data to most recent available IO data in the current study will require significant time and efforts. However, it can be done in any such future assessments to explore the latest situation.

This study used a top-down modeling approach to understand EWF-n. The analysis could be complemented by a combination of spatial biophysical models, like a combination of energy, agriculture, land use, and hydrological models that can be amalgamated with the top-down approach. While this study addresses the EWF security challenge in the Indian context, the framework developed in this study has wider application for any region or nation globally.

The insights at the macro-level could be useful for designing specific sectorial and even sub-sectorial policies. For this, however, the analysis will need to be complemented by assessment of the underlying trends in the EWF-s, social, economic, and environmental attributes at sectorial and sub-sectorial levels.

Conclusions

This study demonstrated the usefulness of an EWF-extended IO model, with modified production functions, for short, medium, and long-term assessment of EWF-s, social, economic, and environmental outcomes resulting from different policy scenarios with varied security considerations (nexus or non-nexus based) to satisfy EWF demand. This paper takes India as a case study to examine a nexus-informed approach to policy making for redressing the EWF security (EWF-s) challenges. This study is one of the first to comprehensively examine the nexus between energy, water and food securities, particularly in the Indian context.

The results obtained from this study establish the significance of a far-sighted approach to policymaking. Further, the analysis of five policy scenarios considered in this study; BAU, ES, WS, FS, and Nexus Scenario; suggests a strong need for actions beyond those envisaged by the current policies, which produces least favorable outcomes overall. Separate sector-specific policy approaches have not yielded superior outcomes overall. Success using these isolated approaches has usually been obtained at the security expense of one or other resource sectors.

The analysis in this study suggest that overall, a nexus approach is most effective in improving aggregated EWF-s outcomes for India, at the same time achieving most superior collective security outcomes for EWF-s, society, economy, and environment. This policy scenario is therefore recommended from a sustainable development perspective. These findings, in turn, suggest to the policy-makers and planners the need for integrated and holistic planning, the successful implementation of which is contingent upon a few factors that this paper has highlighted. The barriers to the successful implementation of the Nexus scenario could be overcome by their inclusion in development plans and sector-specific roadmaps. Lastly, the study provides the limitations of this study and recommends prospective areas for further research.

As India seeks to move forward with its SDGs and Nationally Determined Contributions (NDCs), this study also indicates, an approach to align future planning with the sustainable growth ambitions, given the integral role of these elements in future EWF-s planning and policymaking. The study, finally, reiterates the need for long-term integrated and holistic planning for India and posits that the recommendations derived from this study may benefit the key Indian planning agencies involved in the development and implementation of EWF-s policies in the country.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

As a corresponding author, on behalf of all the named authors, I declare no conflict of interest associated with this publication.

The authors declare no conflict of interest associated with the publication.

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Supplementary materials

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