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Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym

Elias Martinez-Hernandez[a,d,*], Matthew Leach[b], Aidong Yang[c]

[a] Department of Chemical Engineering, University of Bath, Bath BA2 7AY, UK
[b] Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, UK
[c] Centre for Environmental Strategy, University of Surrey, Guildford GU2 7XH, UK
[d] Biomass Conversion Department, Instituto Mexicano del Petróleo, Lázaro Cárdenas 152, Mexico City, 07730, Mexico

HIGHLIGHTS

- New software tool for techno-ecological simulation of local food-energy-water systems.
- Advanced nexus tools by explicit dynamic modelling of techno-ecological interactions.
- Demonstrated the tool by assessing a local synergistic nexus system in a UK eco-town.
- Synergistic design shown to improve local nutrient balance.
- Local integration boosts carbon capture, water reuse, and local energy and food sufficiency.

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ABSTRACT

The water-energy-food (WEF) nexus concept highlights the importance of integrative solutions that secure resource supplies and meet demands sustainably. There is a need for translating the nexus concept into clear frameworks and tools that can be applied to decision making. A simulation and analytics framework, and a concomitant Nexus Simulation System (NexSym) is presented here. NexSym advances the state-of-the-art in nexus tools by explicit dynamic modelling of local techno-ecological interactions relevant to WEF operations. The modular tool integrates models for ecosystems, WEF production and consumption components and allows the user to build, simulate and analyse a "flowsheet" of a local system. This enables elucidation of critical interactions and gaining knowledge and understanding that supports innovative solutions by balancing resource supply and demand and increasing synergies between components, while maintaining ecosystems. NexSym allowed assessment of the synergistic design of a local nexus system in a UK eco-town. The design improved local nutrient balance and meets 100% of electricity demand, while achieving higher carbon capture and biomass provisioning, higher water reuse and food production, however with a remarkable impact on land use.

1. Introduction

Water, energy and food are essential to sustain the development of our society. By 2030, water demand is expected to increase by 40% [1], and energy by 50% [2] and food also by 50% [3] in respect to 2010 levels, mainly due to the increasing population and higher standards of life in developing countries. Under the stressors of climate change, progressive urbanisation and resource scarcity, it is becoming urgent for governments, industries and organisations to secure access to water, energy and food. The corresponding provisioning systems are strongly interrelated [4], with approximately 15% of global water withdrawals used for energy production [5] and 70% for food production [6], while about 3% of global electricity is required for water provision [7] and 6% for food production [6]. The Water-Energy-Food (WEF) nexus concept was presented at the 2011 Bonn Conference as an approach that can support the realisation of Sustainable Development Goals, by reducing trade-offs and encouraging synergistic integration across sectors to achieve WEF security for human well-being with high efficiency levels, while ensuring ecologically sustainable use of resources [8].

The design, analyses and policies for the operation and planning of WEF production and preservation of ecosystems are usually addressed separately [9]. Tackling resource issues of the WEF nexus needs a systems view to couple human and natural systems in order to identify sustainable solutions [10]. Several studies have contributed to this

* Corresponding author.
E-mail addresses: emartinez@imp.mx, e.martinez.hernandez@bath.ac.uk (E. Martinez-Hernandez).

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Table 1
Characteristics of existing Nexus tools and frameworks for integrated modelling and assessment.

Tool	Modelling framework	Scale	System breadth	Analytical capability	Flexibility
GLOBIOM [17]	Dynamic multiregional partial equilibrium model	Global	WEF nexus and other interacting systems such as ecosystems	Geographically-explicit and long-term management of global land uses	Focused on land uses
WEF Nexus Tool 2.0 [19]	Input-output	National	WEF nexus components	Scenario-based for given food self-sufficiency level calculates nexus resource flows and interactions, and greenhouse gas (GHG) emissions	Focused on food as entry point and Qatar country
MuSIASEM [22]	Input-output, nested hierarchical view of the economy	Aggregated to national or sub-national level	WEF nexus components, land, economy, human capital and ecosystems	Accounting of flows and funds and their ratios as indicators. GHG emissions and land-use	Adaptable to various contexts
CLEWS [25]	Integrates detailed models from different tools	Regional	Climate, Land, Energy and Water	Depend on the tools used for the CLEW assessment	Depend on the tools used for the CLEW assessment
Quantitative assessment framework [21]	Input-output based on Lontief matrices	National	WEF nexus components	Scenario-based, accounting of nexus resource consumption and interdependency indicators	Fixed defined technologies and interactions
DEA [24]	Data Envelopment Analysis Model	Local (city level)	WEF nexus components	Input-output efficiency	
PRIMA [26]	Integrates regional climate, hydrology, agri-culture and land use, socioeconomics and energy systems sector models	Regional	WEF components, economy, land use	Climate change related analyses and costs, land use, greenhouse gas emissions	Flexible, portable and modular

coupling and mainly focused on the development of qualitative frameworks and from a policy perspective [11]. In practice, any decision will require first quantification of nexus interactions and analysis in terms of resource implications and ecosystems impact [12]. Identifying critical interactions is also important to leverage synergies that help to balance trade-offs. The motivation for this work is to develop a framework and a tool for integrated resource assessment, accounting for integration within and across WEF subsystems, ecosystem and consumption components that interact in a local system.

Studies approaching the nexus have been presented using various methods, tools and frameworks. Some of the first studies perform accounting and analysis for two-sector linkages (e.g. water-energy [13], food-energy [14]); for example, the SPAtial and Temporal NEXus - Water Energy (SPATNEX-WE) model addresses the water-energy nexus comprehensively [15]. Studies have also been carried out for specific production systems (e.g. tomatoes production [16]). But tools capable of addressing any production systems and all the three nexus components in conjunction are needed to enable more comprehensive assessments. Table 1 shows examples of these kind of tools with a wide variety of scale, scope, flexibility and analytical capability. WEF nexus analyses have so far been mostly applied at large spatial scales such as global [17], regional [18] or national level [19]. For example, the Global Biosphere Management Model (GLOBIOM) has been adopted which allows to consider global diversification of land uses [17]. Multi-Regional Input-Output modelling (MRIO) has been applied to study the WEF nexus in East Asia value chains [20]. The WEF Nexus Tool 2.0 is a scenario-based tool for guiding resource allocation at the country level for a given level of food self-sufficiency and a set of technologies, land uses and resource availabilities [19]. Addressing smaller scales, the WEF nexus has also been analysed for cities and urban environments from a resilience point of view [23]. One recent development is the Data Envelopment Analysis (DEA) Model to evaluate the WEF-Nexus input-output efficiency at the city level [24]. This model allows building a local index system from regional and national data, which is useful when local level data is scarce; but the framework does not deal with interconnections of WEF resources. At the household scale, an integrated model has been proposed to capture the interactions between WEF at the end-use level [29].

A key desirable feature of a nexus analytics tool is its ability to quantify and assess connections between different subsystems. Recently, a quantitative assessment framework has been proposed which considers the inter-sectoral consumption of WEF resources and calculates the variations in total consumption by a country depending on different demands and technology efficiencies [21], but it does not account for inter-sectoral synergies or ecosystem processes. The Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is an analytical framework that consolidates quantitative information about socio-economic metabolism into indicators at different hierarchical levels of the society, based on flows (energy, water, energy and money) and funds (land, population, work force and technological capital) [22]. Two of the more comprehensive and flexible tools in Table 1 are Climate, Land, Energy and Water Strategies (CLEWS) and the Platform for Regional Integrated Modelling and Analysis (PRIMA). CLEWS is a framework that integrates existing simulation tools using a modular structure which allows analysing interactions between interconnected sectors [25]. PRIMA features enhanced domestic resolution, individual sector models and a flexible, portable, and modular platform which facilitates its application to different types of analyses, regions and components [26]. A more exhaustive review of methods, frameworks and tools for nexus can be found in [27,9,11]. An interactive web-based platform for inter-model comparison of existing modelling tools has also been developed [28].

There are several common deficiencies of the existing nexus tools. First of all, many of them handle the connections between the three elements of the nexus, but without the inclusion of the interaction between the ecosystems and the nexus. Furthermore, most of them are