Introduction to the Nexus Solutions Tools and its real-World case studies

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Workshop on the introduction of Integrated Assessment Modelling and understanding the multi-sectoral policy insights
September 22 -23, 2022
Centre for Water Informatics & Technology, LUMS, Lahore
Overview

• Introduction to Nexus concept and models
• NEST:
  ⇒ What is it? Methods, use, data
  ⇒ How to access and use it
• New MESSAGEix-Nexus module, the new NEST
• Our way forward
Climate-Land (food)-Energy-Water Nexus

1. WHEN IS CLEW NEXUS RELEVANT?
2. CURRENT GAPS AND LIMITATIONS
3. RECOMMENDATIONS TO FOSTER THE USE OF NEXUS TOOLS
WEL nexus modelling and open-source

- Recent boom of new models or interlinkages of existing models. Different scales, model configurations (soft link-integrated)
  - Regional assessment, e.g. CLEWS
  - Global analysis, e.g. MESSAGE-GLOBIOM, GAMS

- Clear advantages of modelling and capturing nexus interactions among sectors. Higher uncertainty, difficult to assess: not enough studies to allow comparison, or very different models, not always well documented

- Open-source: code, software, data, analysis results
Sectoral gap – Theme gap

In average good balance in sectoral components

Simple macro-economic assumptions.
Lack of socioeconomic aspects: inequality, individual/corporate choices, governance
Stakeholder engagement → empirical models, ABMs
NExus Solutions Tools (NEST)

Geospatial Database
- River networks
- Climate scenarios
- Human dev. scenarios
- Resource potentials
- Costs and policies
- Existing assets

The NExus Solutions Tool (NEST)

CWatM – Water Resource Assessment
Distributed Hydrological Model
- Soil Moisture Potential
- Runoff / Recharge
- River Routing

Scenario Generator (SSP-RCP scenarios)
Econometric models and scaling tools

MESSAGEix – Resource Planning
Linear Programming Optimization Model
- Land System
- Energy System

Results Database
- Energy system pathways
- Water system pathways
- Land-use pathways
- Investment pathways
- Ecosystem indicators
- Air emissions
The core model

NExus Solutions Tools (NEST)

**Distributed Hydrology**
Community Water Model (CWatM)
(Burek et al., 2018)

**Infrastructure Planning**
MESSAGEix
(Huppmann et al., 2018)

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**Upscaling**
Potential ET
Effective precipitations
Runoff availability

**Downscaling**
Water and land-use

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Integrated Solutions for the Water-Energy Land Nexus

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Minimize total system cost
Water system

Water distribution

- Pumping
- Desalination
- Water deviation

Water demand

- Urban* (and industrial)
- Rural*
- Energy sector
- Land sector

Return flows*

- Urban
- Rural

Water return flows from energy sector

- Wastewater treatment and recycle

Electricity

- Recharge from rivers, canals and crop fields
- Groundwater+
- Seawater
- Internal surface water+
- Storage
- Surface water

Environmental flows

- Hydroelectric potential

Node up node down

* Exogenous
+ Limits are imposed based on information from hydrological model
Energy system

**Power plants**
- Fossil (natural gas, coal, oil, ccs)
- Nuclear
- Biomass & co-firing
- Solar & Wind
- Hydroelectric

**Power transmission**
- Transmission HV (to other nodes)
- Distribution (internal)

**Electricity demand**
- Urban* (and industrial)
- Rural*

**Rural generation**
- Diesel generator
- Small PV
- Ethanol generator

- Bio-fuel^ (ethanol or solid biomass)

**Return flows**
- Water for cooling
- Bio-fuel^ (ethanol or solid biomass)
- Hydroelectric potential

**CO₂ and other emissions**

* exogenous
^ crop residues can be transported as solid biomass or converted in ethanol, technologies not represented here
Land system

Crops

Irrigated
Irrigation systems
Flood
Sprinkler
Drip

Rainfed only

Crop products demand* by country

Total land constraints

Land availability?

CH4, other emissions, water pollutants

Energy sector

Water for bio-fuel production

Crop residues

Biomass transportation/conversion

* exogenous.
? total available area for agriculture based on historical data

Electricity from grid or local generators

Water for irrigation

Irrigation losses

Water for bio-fuel production

Crop residues

Biomass transportation/conversion
Potential applications of the model for policy analysis

• Impacts of reduced resource availability and alternative allocation schemes

• Influence of technology-specific penetration targets on multi-sector development

• Quantification of investments required to meet future demands

• Identification of feasible transformation pathways for achieving socio-environmental objectives

• Effects of cooperative / non-cooperative strategies across countries
Input data

Mapping infrastructure, potentials and policies
- Power generation and Reservoirs (existing and planned)
- Transmission and road networks
- Groundwater pumping capacity
- Wind, PV and hydropower potentials
- Assessment of demands

Installed Hydropower Capacity

Land use and production maps
- Indus water treaty allocations
- Urban water transfers (e.g., Karachi)
- Irrigation technologies local data

Urban and rural water withdrawal and electricity demand

Yield demand

AFG

IND

Urban - withdrawal
Rural - withdrawal
Urban - electricity
Rural - electricity

year
million m$^3$ per day
100
300
2020 2040 2060
million m$^3$ per day
80
120
200
2020 2040 2060
Gigawatts
50
100
200
2020 2040 2060
Gigawatts
10
30
60
2020 2040 2060

Irrigation technologies in local data

- Cotton
- Fodder
- Pulses
- Rice
- Sugarcane
- Wheat
Shaping scenarios

Business-as-usual (or Baseline) with calibrated population, water, energy and crop demand
Projections based on SSP2 database and RCP6.0 climate assumptions

> Research question: what are the costs and implications to achieve SDG in the region?
> Identify sectors, parameters, constraints that can be changed to model specific policies or changes that address the research question

<table>
<thead>
<tr>
<th>BAU</th>
<th>SDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>NDC implementation</td>
</tr>
<tr>
<td>Water treatment/sanitation</td>
<td>Projection of current rates with GDP growth</td>
</tr>
<tr>
<td>Water efficiency</td>
<td>No measures</td>
</tr>
<tr>
<td>Environmental flows</td>
<td>No policy</td>
</tr>
<tr>
<td>Land</td>
<td>Projected trend of flood irrigation use</td>
</tr>
</tbody>
</table>
Model application

Comparing baseline with preliminary SDG 6 + 7 + 13 scenario

Average yearly costs for the entire basin (2020-2050)

- **Indus**
  - Investment
  - Operational

Average yearly cross-sectoral energy, water and biomass flows

- **baseline**
- **multiple SDG**

**Low carbon tech and wastewater distribution and treatment.**
Use of more efficient, but costly irrigation technologies.
Higher land requirements

**Less water used in agriculture**
Much more energy required for pumping, treating, water infrastructure, power plants
Importance of integrated framework

- More efficient solution
- Cost effective
- Take into account synergies

Electricity production under different scenarios

SDG6

SDG7

SDG13

multiple_SDG

• More efficient solution
• Cost effective
• Take into account synergies
Sensitivity

baseline scenario, different SSPs, climate models and climate scenarios (RCP 2.6 and 6.0)

Cost

Internal runoff from CWATM same for all SSP

Water use:
Most noticeable differences among models and scenarios, rather than SSPs

Groundwater extraction

- Water use: Most noticeable differences among models and scenarios, rather than SSPs
Open-source tool

- CWaTM and MESSAGEix are open-source tools, accessible and well documented online (limitation on solvers)
- NEST has its own documentation (Vinca et al., 2020, GMD) open Github repository, interactive scenario explorer
- Limitations: Availability vs accessibility/user friendly. Data
- Different audience:
  ⇒ scientific: interest in data and model
  ⇒ policy makers: interested in interactive tools

https://github.com/iiasa/NEST
https://data.ene.iiasa.ac.at/nexus-basins/
http://vinca.shinyapps.io/indus_explorer

Geoscientific Model Development
An interactive open-access journal of the European Geosciences Union

The Nexus Solutions Tool (NEST): An open platform for optimizing multi-scale energy-water-land system transformations

Adriano Vinca1,2, Simon Parkinson1,2, Edward Byers2,3, Peter Burek2,4, Zarrar Khan3, Volker Krey4,5, Fabio A. Diuana2,4, Yaoping Wang3, Asnir Ilyas4, Alexandre C. Köberle2,5, Iain Staffell5, Stefan Pfenninger2, Abubakr Muhammad6, Andrew Rowe2, Roberto Schaeffer5, Narasimha D. Rao4,10,11, Yoshihide Wada6,11, Ned Djilali2, and Keywan Riahi1,12
Access, download and run NEST

Prerequisites:

• GAMS with active license, R, (Rstudio recommended), download and install the gdxrrw R package from [here](https://github.com/iiasa/NEST)

• Check paths: GAMS, R

1. Download (or clone with Github) the folder from: [https://github.com/iiasa/NEST](https://github.com/iiasa/NEST)

2. Unzip the folder

3. Open the R project and `multiple_scenario_new.r`

4. Define path: INDUS_IX_PATH (and restart Rstudio), update GAMS path in `basin_msggdx.r`

5. RUN

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**Scenario names**

- baseline0
- baseline
- no_planned_hydro
- baseline_coop
- no_hydro_EMI_res
- SDG6

**Policy options**

- # SDG6
- # GHG Emission
- # SDG7: solar/wind target
- # groundwater extraction
- # constraint available land
- # change food demand, cust...
MESSAGEix-Nexus
Module of the MESSAGEix-GLOBIOM family

Water System
- Water availability
- Sectoral water demands
- Supply & distribution
- Water table depth

Land System
- Irrigation water
- Crop efficiency
- Crop types
- Biomass trajectories

Harmonization & upscaling

Water Sector
~202 regions/basins

Energy Sector
11 region

*ISIMIP Output data from Global Hydrological Models - https://www.isimip.org/
Approach: MESSAGEix-GLOBIOM IAM

Climate policy

2.6 W/m² target

SDG measures

Food
Heathy (EAT-Lancet) diet, reduce food waste

Water
Efficiency improvements, environmental flow constraints, piped water access, wastewater treatment

Energy
Maximized electrification, phase-out traditional bio, cooling gap

Life on land
Protected natural land (>30%)

Climate impacts

RCP 2.6, 6.0

- Hydrology: Precipitation pattern/runoff, groundwater intensity
- Crop Yield changes
- Renewable energy
- Cooling/heating demand
- Desalination potential
- Power plant cooling capacity

Based on: Doelman et al. 2022, MESSAGE-ACCESS, Van Vuuren et al., 2019, Parkinson et al., 2019, Frank et al., 2021, Hasegawa et al., 2015, Pastor et al., 2019
## Approach – Climate Impacts

<table>
<thead>
<tr>
<th>Climate impact</th>
<th>Approach</th>
<th>IMAGE</th>
<th>MESSAGEix-GLOBIOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renewable supply (wind, PV, CSP, hydro, bioenergy)</td>
<td>Different costs supply curves based on 0.5x0.5 grid calculations</td>
<td>Yes</td>
<td>Yes, hydropower only</td>
</tr>
<tr>
<td></td>
<td>[Gernaat, et al. 2021]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating / cooling demand</td>
<td>Impact via population weighted HDD, CDD based on 0.5 x 0.5 grid</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>[Byers, et al. 2018]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water availability</td>
<td>Runoff and groundwater recharge from LPJmL calculated at 0.5 x 0.5 grid</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>[Frieler et al., 2017]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop yields</td>
<td>IMAGE: Crop yield change due to climate change calculated in LPJmL on 0.5 x 0.5 grid [Schaphoff et al., 2018 ]</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>MESSAGE-GLOBIOM: Crop yields from [Byers et al., 2018] are used in the GLOBIOM model.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power plant cooling &amp; desalination potential</td>
<td>Power plant cooling: van Vliet 2016</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Desalination: specific analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario</td>
<td>Climate Forcing (W/m²)</td>
<td>SDGs</td>
<td>Impacts</td>
</tr>
<tr>
<td>-------------------</td>
<td>------------------------</td>
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<tr>
<td>SSP2-noCF</td>
<td>6.0</td>
<td>No additional effort</td>
<td>Frozen to 2020</td>
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<tr>
<td>SSP2-26-SDG-CF</td>
<td>2.6</td>
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</tr>
<tr>
<td>SSP2-26-CF</td>
<td>2.6</td>
<td>No additional effort</td>
<td></td>
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</table>

SSP2 – Middle of the Road Socio Economic Pathway  
CF – Climate Feedback
Access MESSAGEix-Nexus (in progress)

MESSAGEix
https://github.com/iiasa/message_ix

MESSAGEix-GLOBIOM model
https://github.com/iiasa/message-ix-models/

documentation

https://docs.messageix.org/projects/models/en/latest/
Upcoming work - Flexibility across scales

MESSAGEix (Global)

Downscale/Prototype (existing method)

MESSAGEix-Country

Updated country scale model with water representation as in global model

Add water-nexus to the country model

MESSAGEix-Nexus (National/Basin)

NEST Indus (Basin)

Improve existing model structure to be flexible to other regions in future

Bottom-up approach/sub-catchment level
# The way forward

## Summary of Key Challenges & Recommended Actions

### Scope & Definition

**Key Challenges**
- Vague definition can be barrier to applications
- Restrictive definition could hamper developments

**Recommended Actions**
- Establish nexus community of practice
- Establish online platform to maintain, curate and share nexus knowledge
- Hold expert workshops to discuss scope & definition
- Maintain evolving nexus definitions & scope on nexus platform

### Methodology

**Key Challenges**
- Lack of access to nexus data across sectors and scales is an issue
- Numerous methodologies without a comparison framework

**Recommended Actions**
- Create open-source central nexus data repository with standardized data units
- Organize inter-model comparison with controlled case studies
- Online dashboard to communicate inter-model results to public

### Application

**Key Challenges**
- Limited explicit nexus implementation in practice
- Lack of nexus metrics & policy instruments
- Lack of communication between science, policy & public

**Recommended Actions**
- Maintain nexus success stories and failures in online platform to promote applications
- Establish clear nexus metrics and reporting mechanisms to be used by funders and governments as well as for impact and project assessments

### Future Directions

**Key Challenges**
- Inertia & existing siloed structure of institutions
- Tradeoffs between sectors & stakeholders
- Short terms of policymakers
- Lack of training & public awareness

**Recommended Actions**
- Maintain list of short and long-term nexus challenges and goals with corresponding links to relevant actions, data, case studies and knowledge on the nexus platform

Kahn et al., 2022, Frontiers in Environmental Science
Main conclusions

• Integrated analysis gives more complete answers than single sector assessments

• Difficult to compare/validate results: More multi-model intercomparison is needed; Need for more shared common assumptions in modelling community (like SSP, SDG for water and land)

• Open-source, where to focus our efforts: code, data or interactive tools?
  ⇒ Scientists: data, well documented code/software
  ⇒ Policy makers: simplified interactive models, results visualization explorers
Thank you very much for your attention!

For more detail about the model, scenarios and results:

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**Transboundary cooperation a potential route to sustainable development in the Indus basin**

Adriano Vinca, Simon Parkinson, Keywan Riahi, Edward Byers, Afreen Siddiqi, Abubakr Muhammad, Ansir Ilyas, Nithiyandanam Yoganwaran, Barbara Willaarts, Piotr Magnuszewski, Muhammad Awais, Andrew Rowe and Ned Djilali

**Climate-Land-Energy-Water Nexus Models Across Scales: Progress, Gaps and Best Accessibility Practices**

Adriano Vinca, Keywan Riahi, Andrew Rowe and Ned Djilali

1International Institute for Applied Systems Analysis, Laxenburg, Austria, 2Institute for Integrated Energy Systems, University of Victoria, Victoria, BC, Canada
Back up slides
Multiple objective scenario: water use

Mostly nuclear replacing fossil fuel, cooling technologies with low water consumption (e.g. air cooling)