Integrated Assessment Modeling for Sustainable Transformations in the Indus

Dr Talha Manzoor
Assistant Professor and Associate Director (Operations)
Centre for Water Informatics and Technology (WIT), LUMS

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COMMITTED

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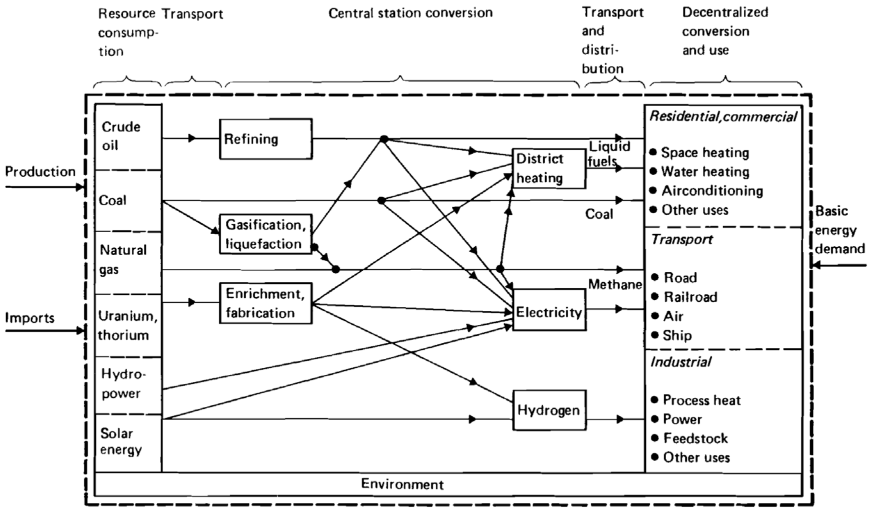
The MESSAGE Energy Supply Model

- Developed in the 1970's at IIASA's Energy Systems Program group
- MESSAGE is a dynamic linear programming model that minimizes the total discounted costs of supplying a given set of energy demands over a given time horizon.



Acronym: Model for energy supply systems alternatives and their general environmental impact

International Institute for Applied Systems Analysis (IIASA)

Sectoral Decision Making: Energy Supply systems

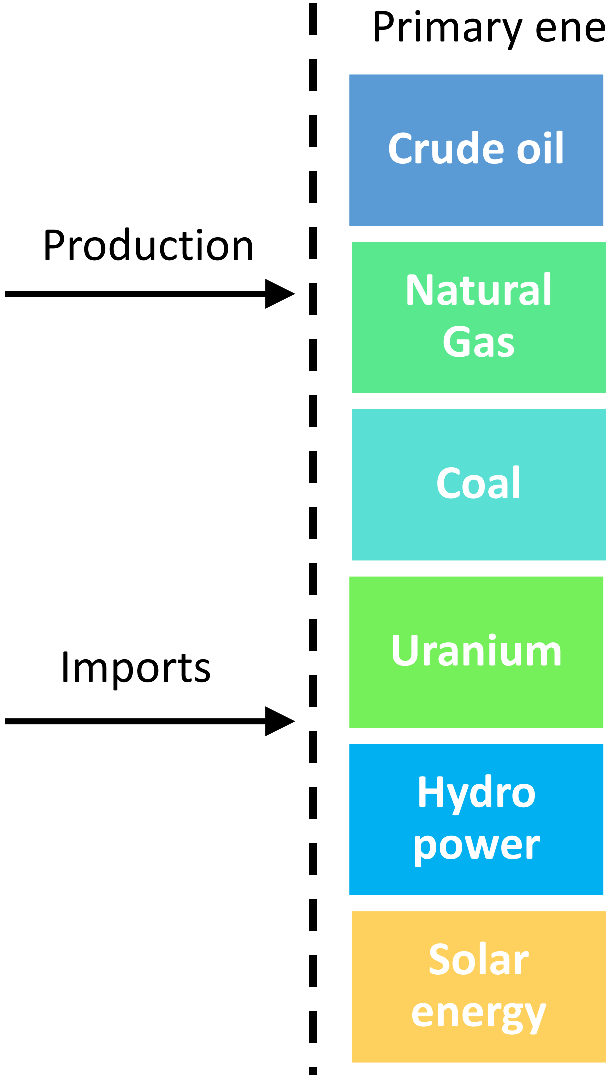
Multiple technologies for energy production exist

- Fossil fuels
- Nuclear Energy
- Solar Energy
- Hydro power
- Geo-thermal
- And so on. . .

The purpose of ESS models is to determine the optimal mix of technologies over the next 25-50 years

Resource consumption subsystem

Primary energy resources – $j \in \{1, \ldots, m\}$



Dynamics

$$z_j(t+1) = z_j(t) + w_j(t)$$

Constraint

$$z_j(t) \leq \bar{z}_j(t)$$

Resource availability

$$\begin{bmatrix} \bar{z}_1(t) \\ \bar{z}_2(t) \\ \vdots \\ \bar{z}_m(t) \end{bmatrix}$$

$z_j(t)$ the cumulative amount of resource j extracted by the beginning of period t

$\bar{z}_j(t)$ the total amount of resource j available for period t

$w_j(t)$ the total consumption of primary resource j in period t

Energy end-use applications

Demand vector

$$\begin{bmatrix} d_1(t) \\ d_2(t) \\ \vdots \\ d_L(t) \end{bmatrix}$$

Demand Category – l

Residential, commercial

- Space heating
- Water heating
- Airconditioning
- Other uses

Transport

- Road
- Railroad
- Air
- Ship

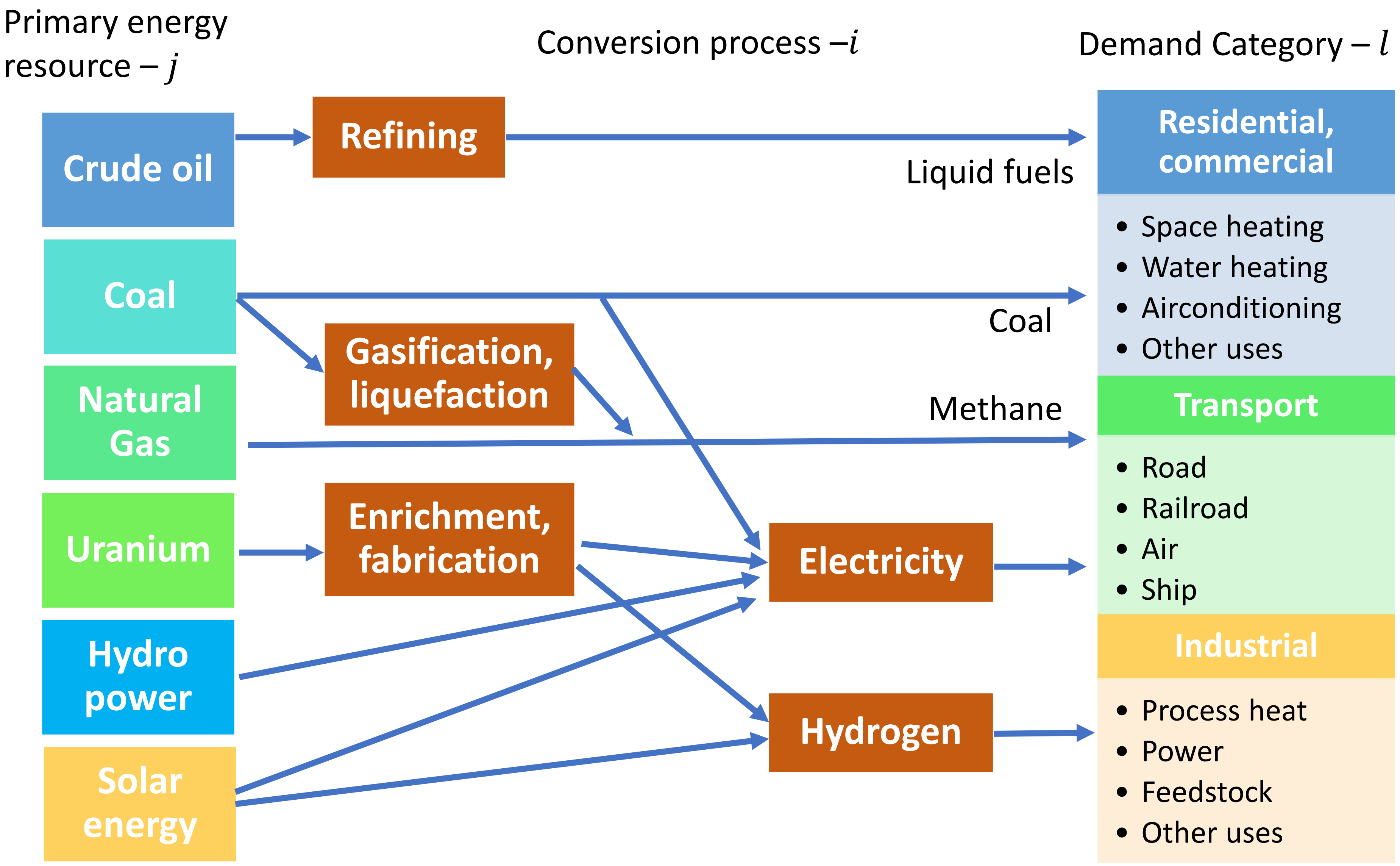
Industrial

- Process heat
- Power
- Feedstock
- Other uses

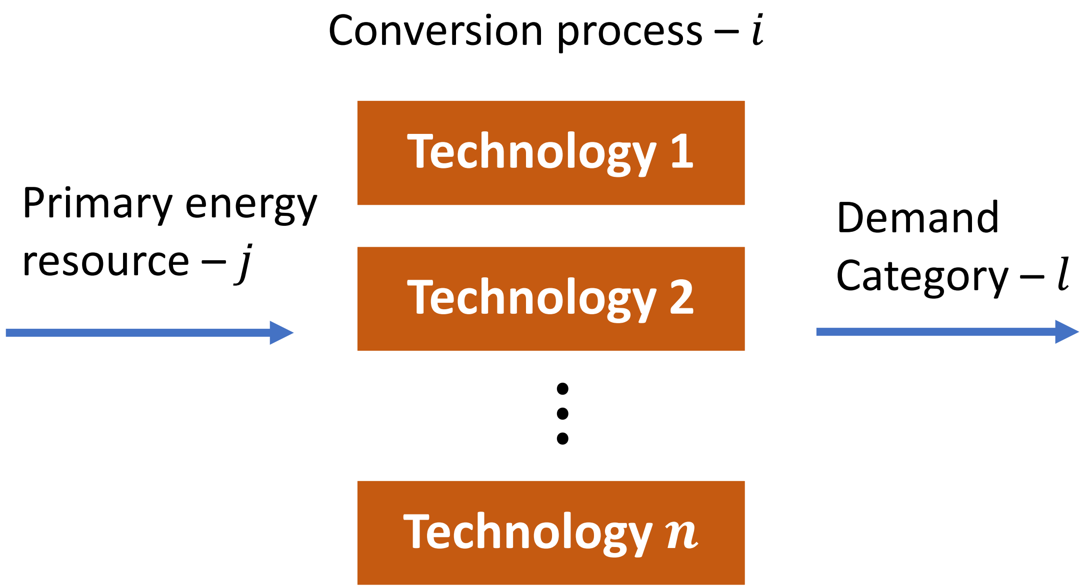
Basic Energy Demand ←

- Electricity
- Methane
- Natural gas
- Hydrogen

Energy conversion processes



Energy conversion processes



Dynamics

$$y_i(t+1) = y_i(t) + v_i(t) - v_i(t-\tau_i)$$

Constraints

$$u_i(t) \leq y_i(t) \qquad v_i(t) \leq \bar{v}_i(t)$$

Utilization

$$\begin{bmatrix} u(t) \\ u_2(t) \\ \vdots \\ u_n(t) \end{bmatrix}$$

Production capacity

$$\begin{bmatrix} y_1(t) \\ y_2(t) \\ \vdots \\ y_n(t) \end{bmatrix}$$

Investment

$$\begin{bmatrix} v_1(t) \\ v_2(t) \\ \vdots \\ v_n(t) \end{bmatrix}$$

Objective Function

$$J = \sum_{t=0}^{T-1} \beta(t) \left[\sum_{i=1}^{n} {}^{u}c_i u_i(t) + \sum_{i=1}^{n} {}^{v}c_i v_i(t) + \sum_{j=1}^{m} {}^{w}c_j w_j(t) \right] \to \min$$

Cost of investment

Cost of utilizing a process

Cost of resource extraction

Optimization Problem

Objective

$$J = \sum_{t=0}^{T-1} \beta(t) \left[\sum_{i=1}^{n} {}^{u}c_i u_i(t) + \sum_{i=1}^{n} {}^{v}c_i v_i(t) + \sum_{j=1}^{m} {}^{w}c_j w_j(t) \right] \to \min$$

State Equations

$$y_i(t+1) = y_i(t) + v_i(t) - v_i(t - \tau_i)$$

$$z_j(t+1) = z_j(t) + w_j(t)$$

Constraints

$$\sum_{i,l} \beta_{jil} x_{jil} = w_j(t) \qquad \sum_{j,l} \gamma_{jil} x_{jil} = u_i(t) \qquad \sum_{j,i} \alpha_{jil} x_{jil} \geq d_l(t)$$

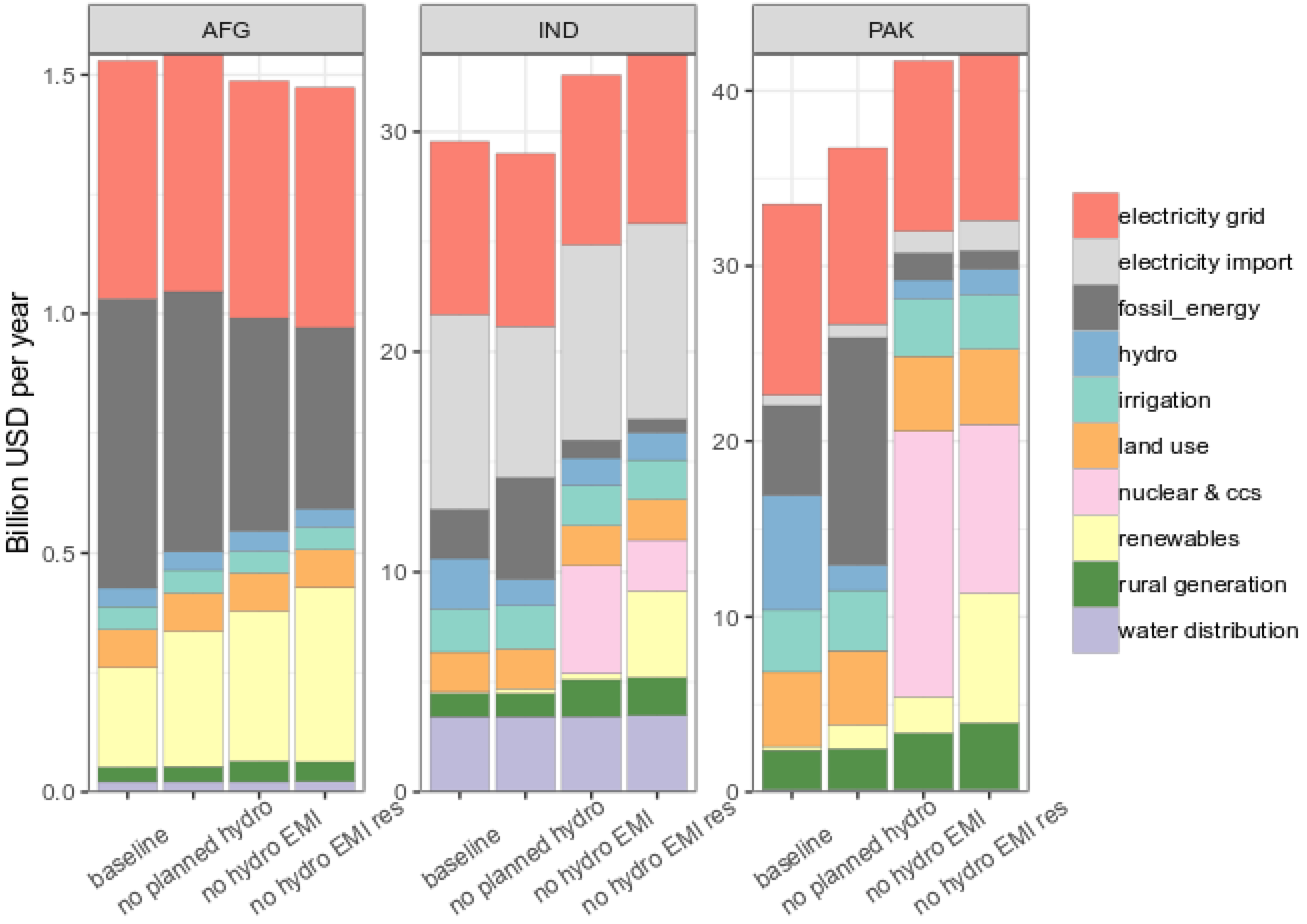
$$z_j(t) \leq \bar{z}_j(t) \qquad u_i(t) \leq y_i(t) \qquad v_i(t) \leq \bar{v}_i(t)$$

Decision variables

$\{x_{jil}(t)\}$ Technology activities

$\{v_i(t)\}$ Technology investments

Typical Output



Analysis using MESSAGEix: Input and Output Data

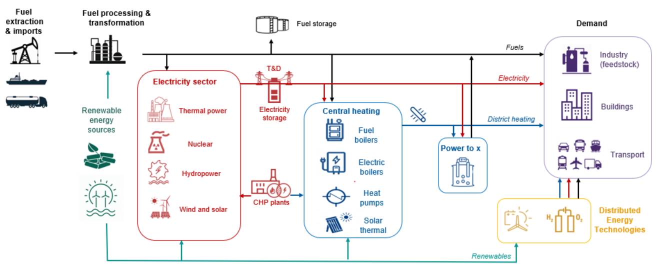
Model input data and output results

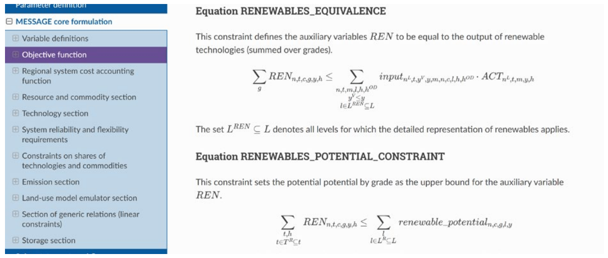
- Technology-rich, bottom-up model
- Suitable for analyzing energy transitions and GHG scenarios over several decades

Input data & Assumptions

- Technologies & resources
- Technical data (lifetime, capacity factor, efficiencies)
- Economic data (capital costs, O&M cost, discount rate)
- Emission factors
- Fossil fuel reserves & resources
- Renewable potential
- Energy balances (historical generation & activity)
- Demand for energy services (Long-term forecasting)

Core Model





MESSAGE core formulation
Variable definitions
Objective function
Regional system cost accounting function
Resource and commodity section
Technology section
System reliability and flexibility requirements
Constraints on shares of technologies and commodities
Emission section
Land-use model emulator section
Section of generic relations (linear constraints)
Storage section

Equation RENEWABLES_EQUIVALENCE

This constraint defines the auxiliary variables REN to be equal to the output of renewable technologies (summed over grades).

$$\sum_{g} REN_{n,t,c,g,y,h} \leq \sum_{n,t,m,l,h,h^{OD}} input_{n^L,t,y^V,y,m,n,c,l,h,h^{OD}} \cdot ACT_{n^L,t,m,y,h}$$

The set $L^{REN} \subseteq L$ denotes all levels for which the detailed representation of renewables applies.

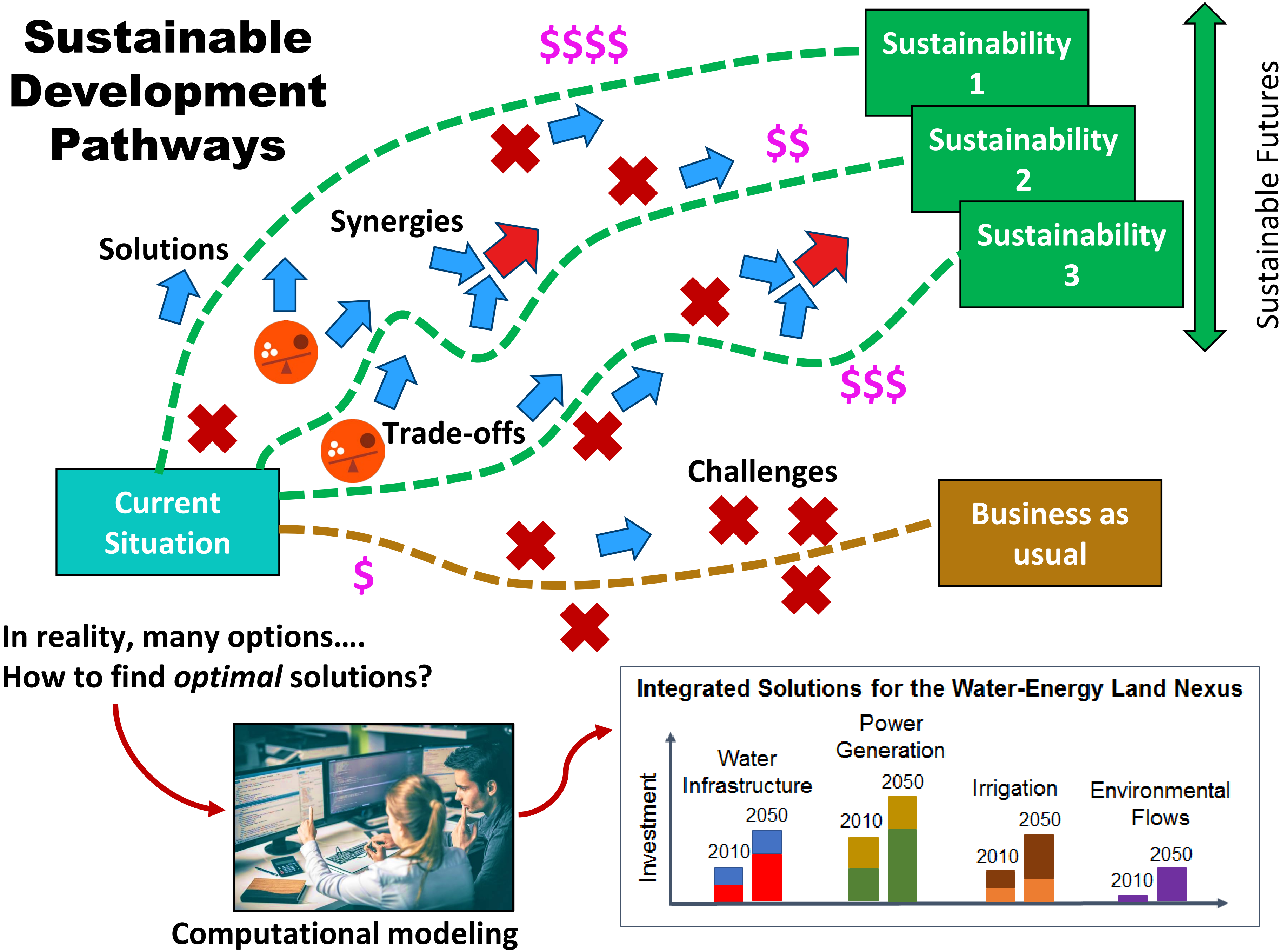
Equation RENEWABLES_POTENTIAL_CONSTRAINT

This constraint sets the potential potential by grade as the upper bound for the auxiliary variable REN.

$$\sum_{t,h} REN_{n,t,c,g,y,h} \leq \sum_{l} renewable\_potential_{n,c,g,l,y}$$

Model Output

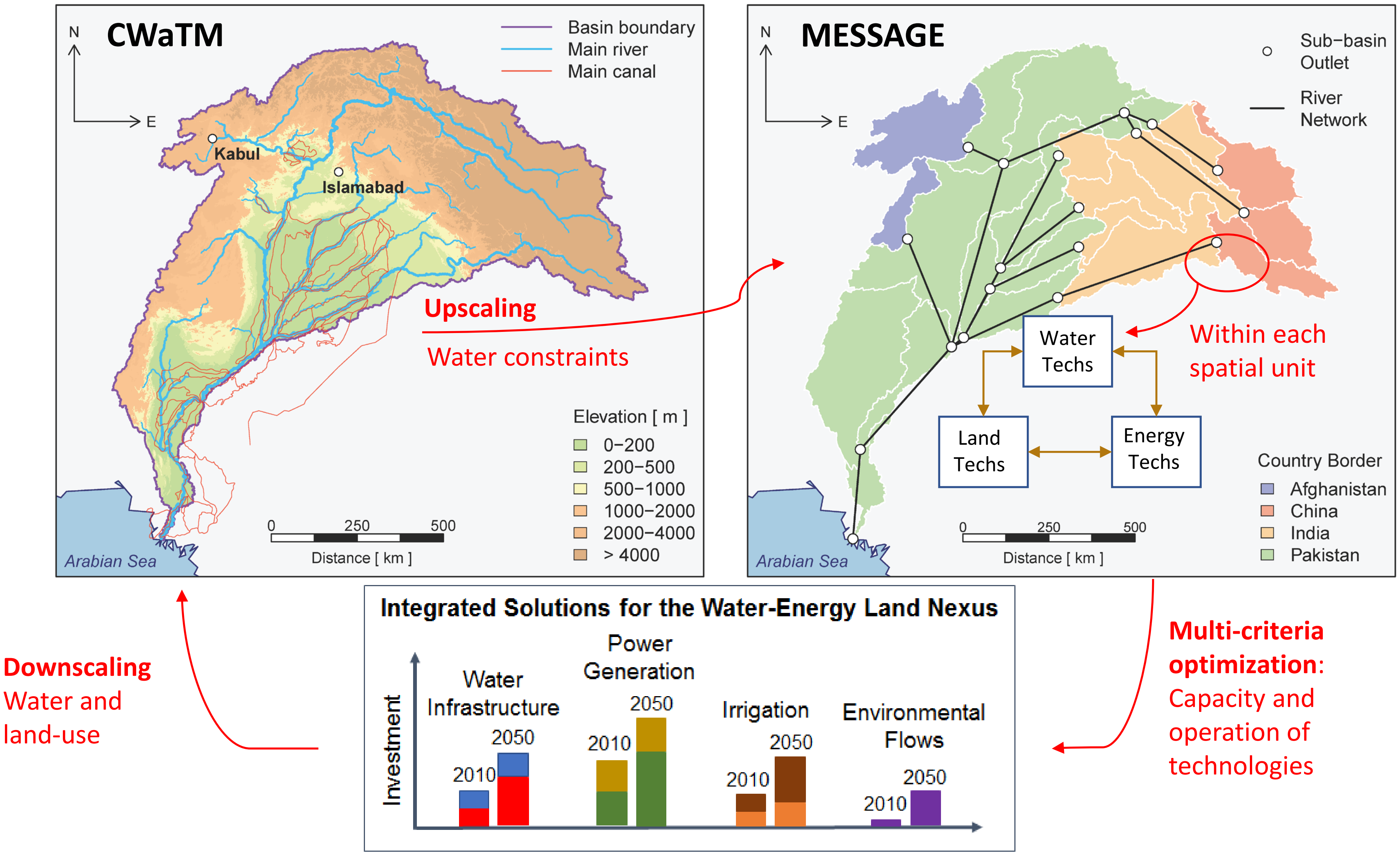
- Installed capacities
- Activities, generation & losses
- GHG & other Emissions
- Sectoral transitions (e.g electricity)
- Final & primary energy
- Share of renewables
- Energy import/export
- Energy Prices


Sustainable Development Pathways
$$$$
Sustainability 1
$$
Sustainability 2
Sustainability 3
Sustainable Futures
Solutions
Synergies
$$$
Trade-offs
Challenges
Current Situation
Business as usual
$
In reality, many options….
How to find optimal solutions?
Computational modeling
Integrated Solutions for the Water-Energy Land Nexus
Investment
Water Infrastructure
Power Generation
Irrigation
Environmental Flows
2010
2050
2010
2050
2010
2050
2010
2050

Project

- Integrated Solutions for Water, Energy and Land (ISWEL)
- IIASA, Global Environment Facility (GEF) and United Nations Development Organization (UNIDO)
- Sub-project on the Indus Basin
- Integrated solutions to water, energy, food and ecosystem security

The NExus Solutions Tool (NEST)
Multi-scale modeling for transforming systems



Vinca, Adriano, Simon Parkinson, Edward Byers, Peter Burek, Zarrar Khan, Volker Krey, Fabio A. Diuana et al. "The NExus Solutions Tool (NEST) v1. 0: an open platform for optimizing multi-scale energy–water–land system transformations." *Geoscientific Model Development* 13, no. 3 (2020): 1095-1121.

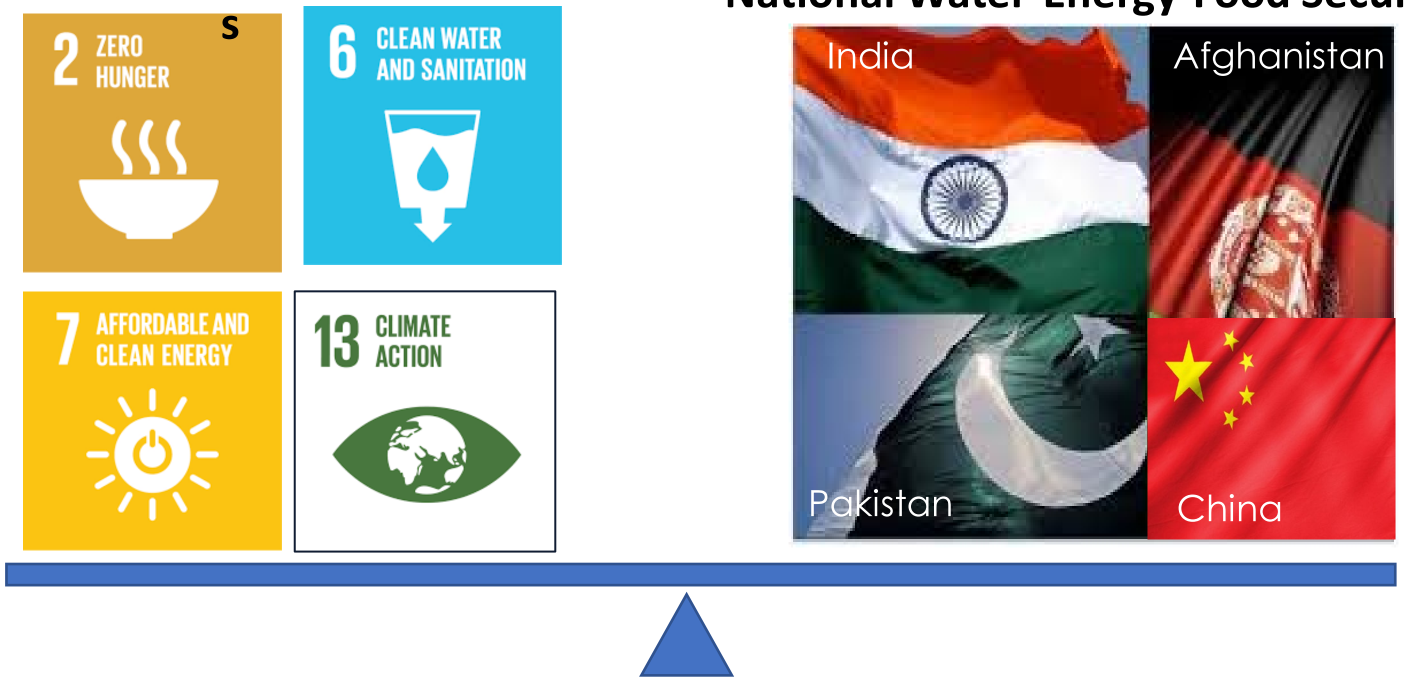
Indus Analysis

How to strike a balance between objectives?

… and at what cost?

SDGs

Transboundary Agreements &
National Water-Energy-Food Security



Scenarios

Name	Description	Type	Constraints
Baseline	No SDG targets; no environmental constraints; expansion of planned hydropower; follow historical trends and agriculture practices (SSP2, RCP 6.0 for all scenarios)	Reference scenario	Planned hydropower in 2030; Land use and irrigation choice (mostly flood)
Multiple objective	SDG related targets: water access and treatment, energy water impacts and GHG emissions Regional targets identified within this analysis: smart irrigation, environmental flow, hydropower expansion	Reference scenario	Water treatment + piped distribution, no once through cooling GHG emissions, +100% environmental flow 50% smart irrigation, planned hydropower in 2030
Extreme climate	90th percentile of runoff distribution when aggregating yearly values from the hydrological model	Sensitivity case	90th percentile on runoff distribution
Basin cooperation	Electricity trade between basin countries cross boundary canals different river allocation than Indus Water Treaty Crop products demand at basin scale, instead of country	Sensitivity case	Release constraints on cross border transmission/canals Release IWT constraints Basin food demand
Economy	SDG targets (water access and treatment); optimal land allocation and diversion from historical trends; expansion of planned hydropower no environmental constraints	Stakeholder pathway	Water treatment + piped distribution +50% environmental flow; Planned hydropower in 2030
Environment	Achieve SDG 6 and 7; No hydropower expansion; Constraints on GHG emission, environmental flow and groundwater use. Deployment of smart irrigation technologies	Stakeholder pathway	Water treatment + piped distribution GHG emission constraint; +200% environmental flow; 50% smart irrigation

Transboundary Cooperation in Indus River Basin

nature sustainability

ARTICLES

https://doi.org/10.1038/s41893-020-00654-7

Check for updates

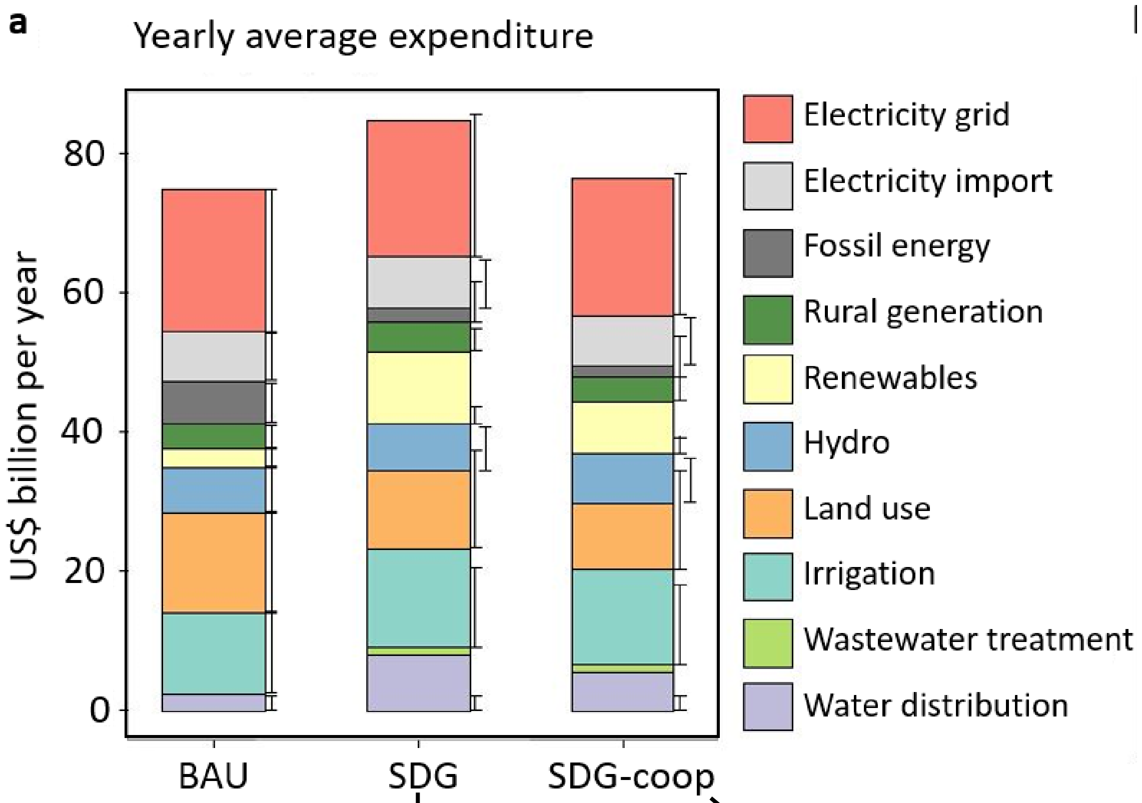
Transboundary cooperation a potential route to sustainable development in the Indus basin

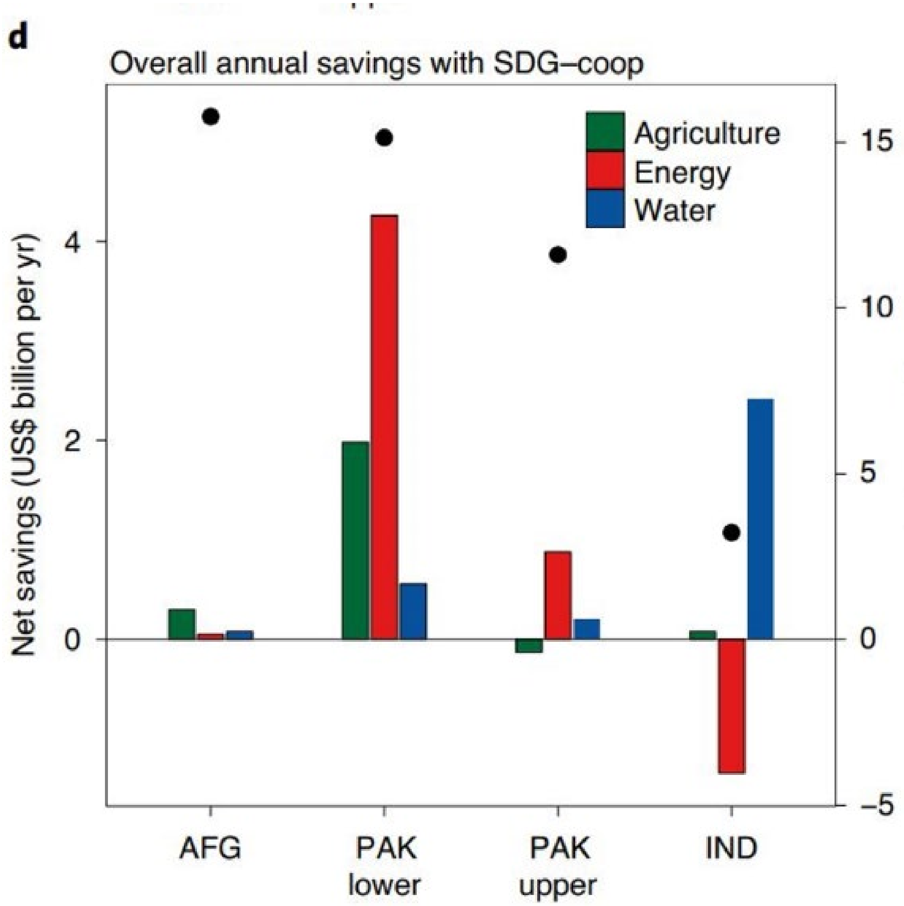
Adriano Vinca[1,2], Simon Parkinson[1,2], Keywan Riahi[1,2,3], Edward Byers[1], Afreen Siddiqi[4,5], Abubakr Muhammad[6], Ansir Ilyas[6], Nithiyanandam Yogeswaran[7], Barbara Willaarts[1], Piotr Magnuszewski[1], Muhammad Awais[1,2], Andrew Rowe[2] and Ned Djilali[2,8]

How the countries in the Indus river basin could lower the costs for development and reduce water stress by cooperating on water resources and electricity and food production?

Yearly costs under different scenarios

Indus Countries, Pakistan, India, Afghanistan, and China





SDG: Indus Countries Meet sustainable Development goals individually

SDG-coop: Indus Countries Meet sustainable Development by cooperating each other

Future Scenario For Indus River Basin

What are benefits and consequence of adopting smart irrigation and hydropower penetration in Indus River Basin?

	Scenario				
Policy mechanism	Baseline	Hydro	Balance-0	*Smart-50*	*Balance-50*
Water conservation	No conservation targets for irrigation.	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).	Minimum flow in Indus delta area of **46Mm^3/d** (July-October) and **12Mm^3/d** (October-March).
Smart irrigation	No smart irrigation technology is available	No smart irrigation technology is available	Smart irrigation is deployed if **cost optimal**.	By 2030, **50% of irrigated area** in each model region is utilizing smart technology.	By 2030, **50% of irrigated area** in each model region is utilizing smart technology.
Hydropower penetration	In future, Install **all planned** hydropower projects in the Basin.	In future, Install **all planned** hydropower projects in the Basin.	In future, Install **all planned** hydropower projects in the Basin.	In the future **no new** hydropower installed in the system.	In future, Install **all planned** hydropower projects in the Basin.
				Crop activities can utilize all available cropping areas and can be **shifted within countries**.	Crop activities can utilize all available cropping areas and can be **shifted within countries**.

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journal homepage: www.elsevier.com/locate/envsci

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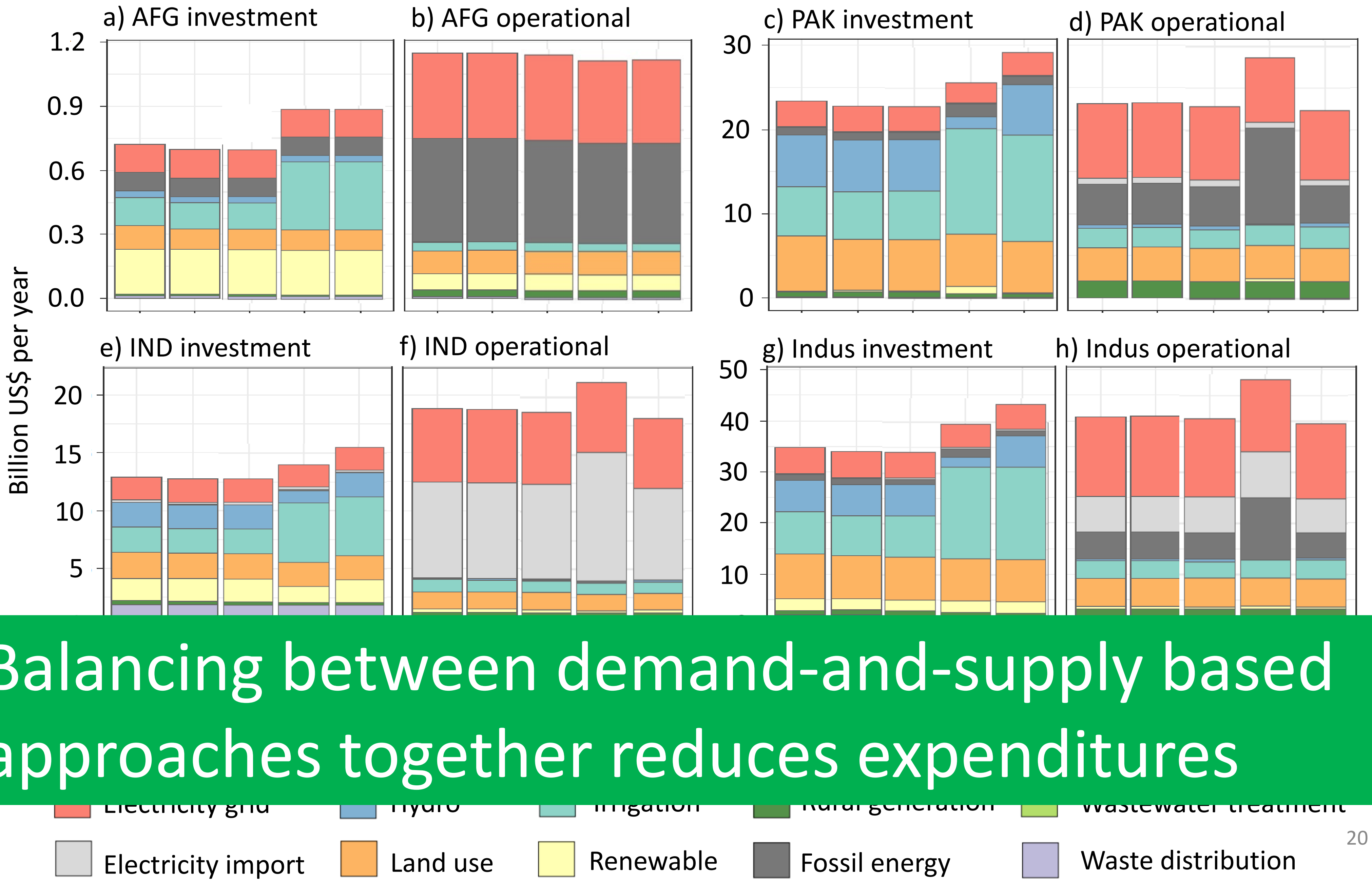
Balancing smart irrigation and hydropower investments for sustainable water conservation in the Indus basin

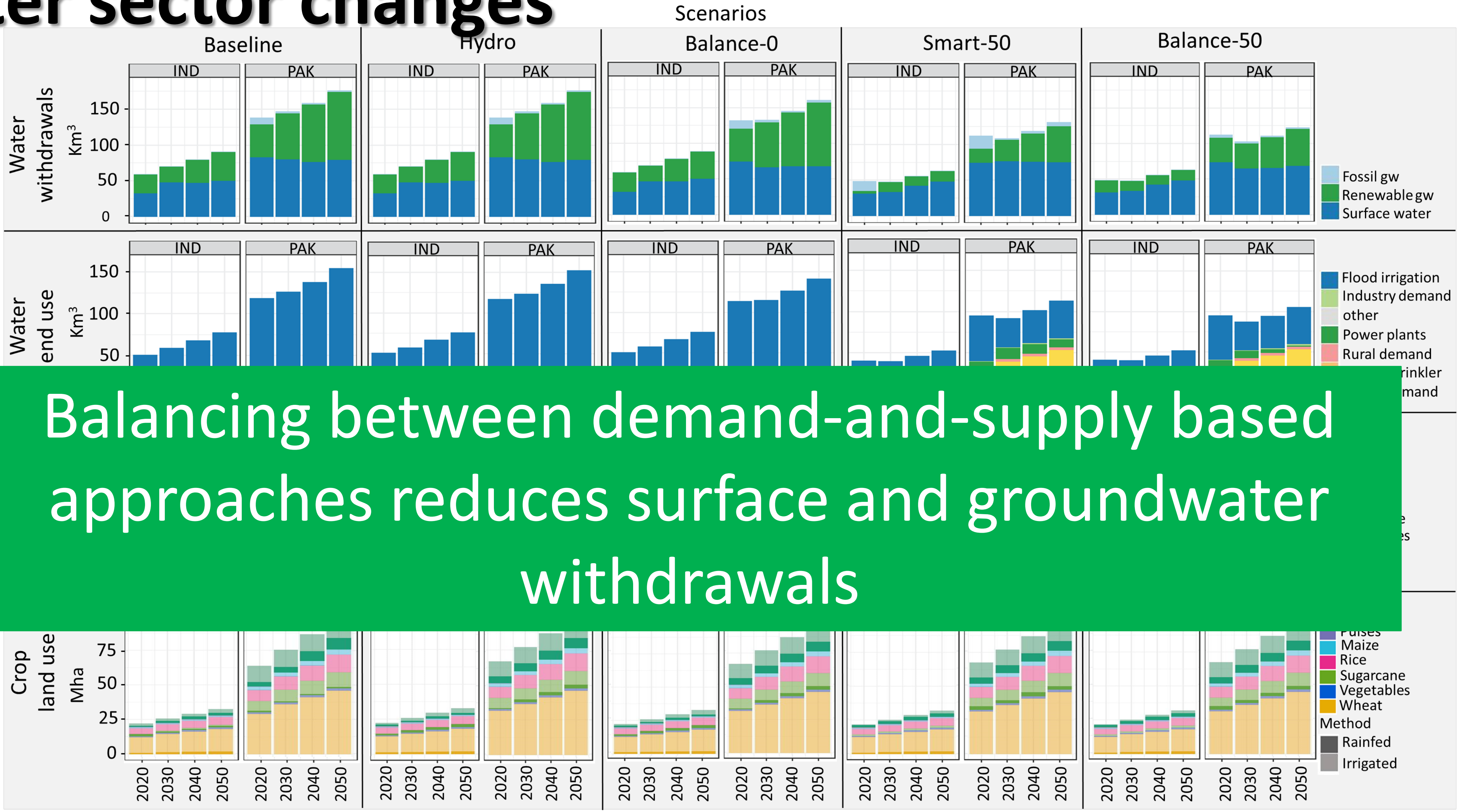
Ansir Ilyas[a,*], Simon Parkinson[b,c], Adriano Vinca[b,c], Edward Byers[b], Talha Manzoor[a], Keywan Riahi[b,c,e], Barbara Willaarts[b], Afreen Siddiqi[d], Abubakr Muhammad[a]

Investment portfolio



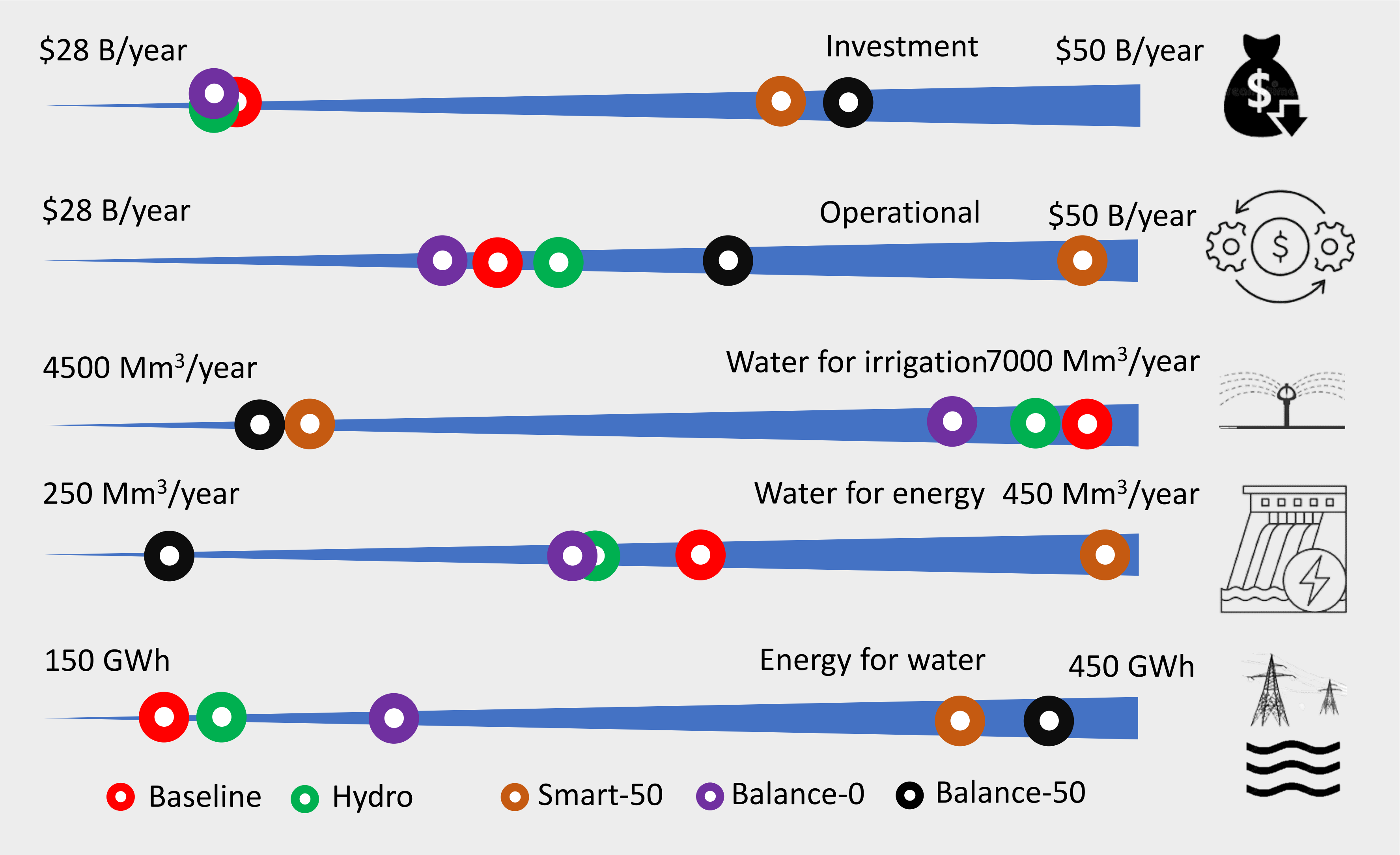
Balancing between demand-and-supply based approaches together reduces expenditures

Water sector changes



Balancing between demand-and-supply based approaches reduces surface and groundwater withdrawals

Comparison of all scenarios



MESSAGEix-Pakistan

"National-level energy model developed using the MESSAGEix framework to generate sustainable pathways for a low emission future for Pakistan"

Current Trends*

- Planned projects (Hydropower mostly)
- Increased import of coal, crude oil
- High reliance on natural gas

Proposed NDCs**

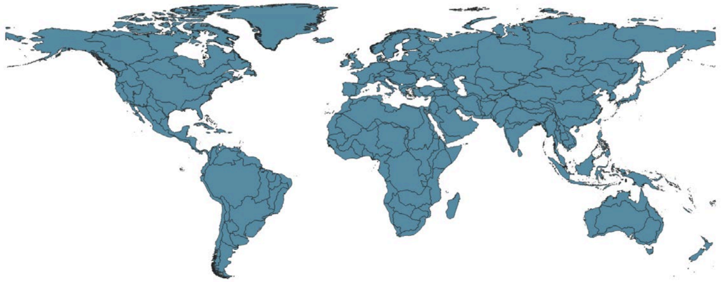
- 20% renewable energy by 2025 & 30% by 2030
- Sectoral actions account for 6.4 Mt CO2eq emissions reduction by 2030
- Lower Vehicle emissions using improved fuel

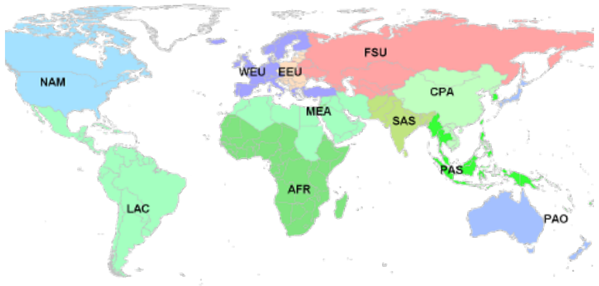
Paris Aligned Scenarios

- Define emission goals consistent with Paris
- Consistent with regional emissions targets
- Burden Sharing tests

Current work

MESSAGEix-Nexus (Global)





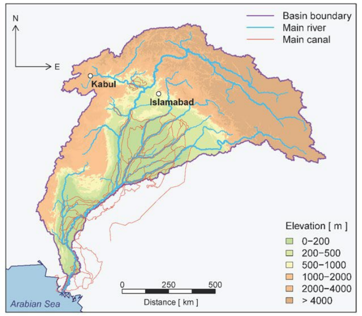
Downscale/Prototype (existing method)

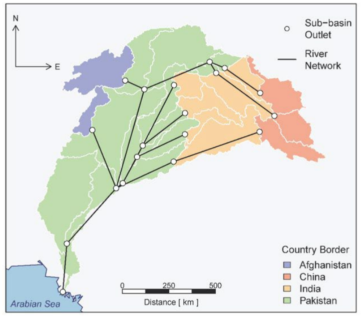
MESSAGEix-Country

Updated country scale model with water representation as in global model

Top-down approach to downscale energy & water components from national model

NEST Indus



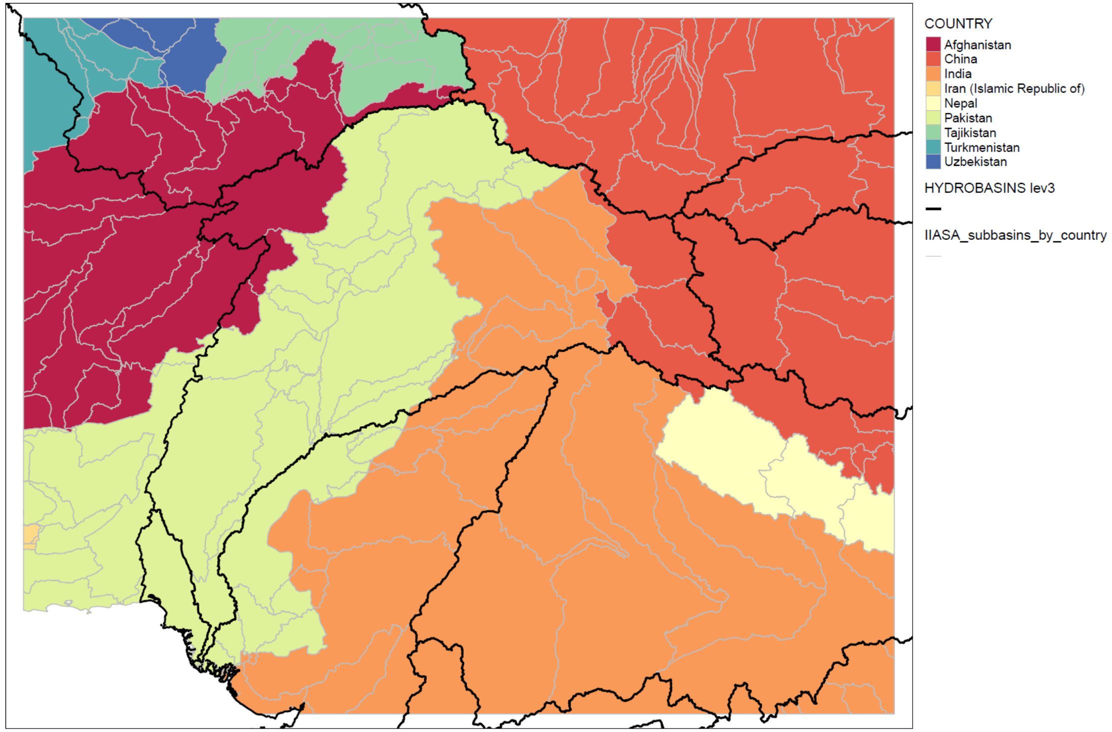


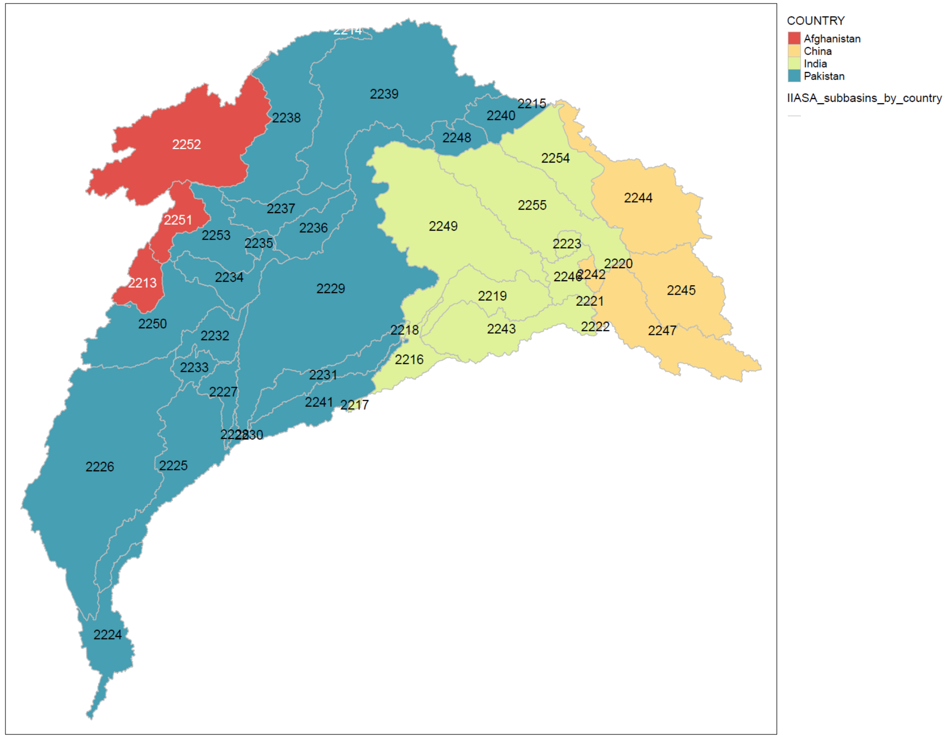
Improve existing model structure to be flexible to other regions in future

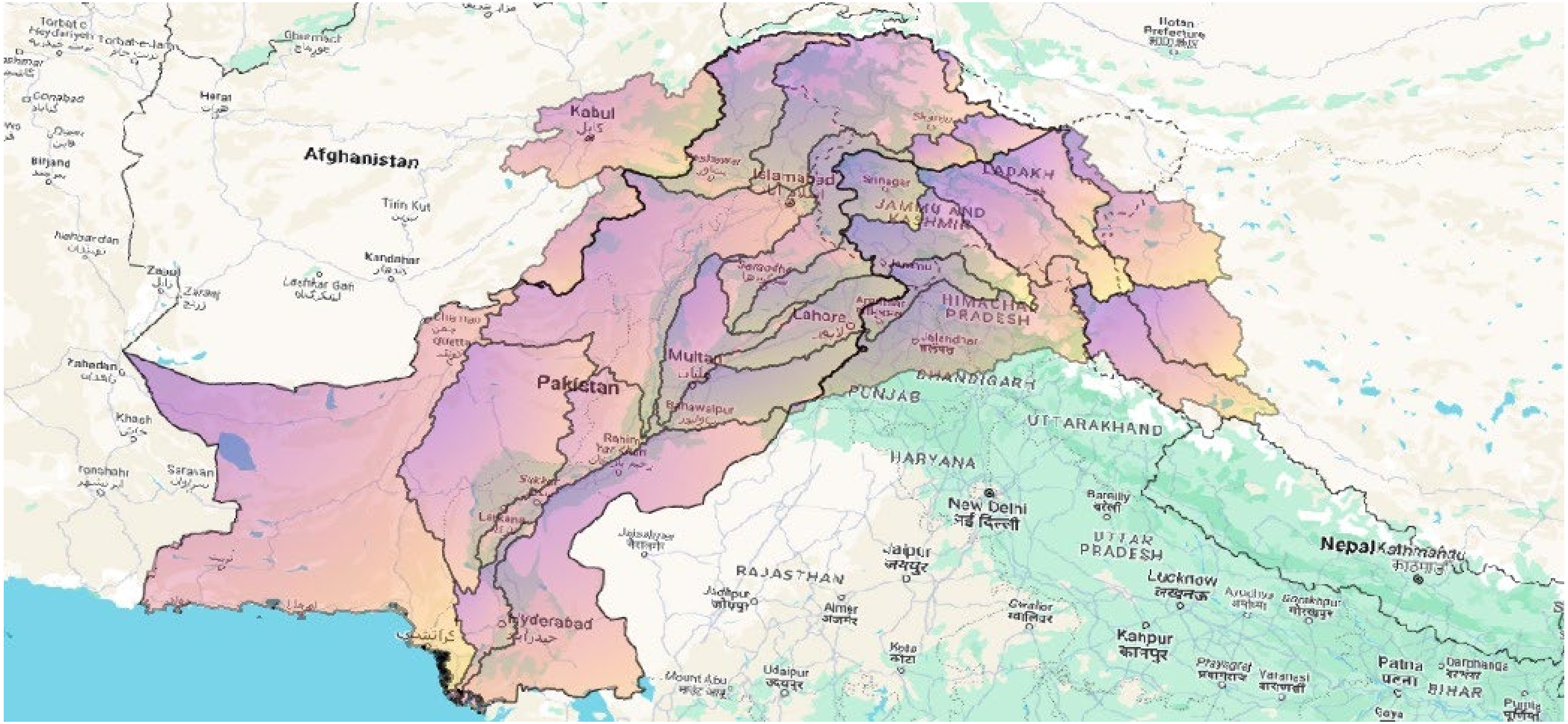
Bottom-up approach/sub-catchment level

MESSAGEix-Nexus (National/Basin)

Spatial Units







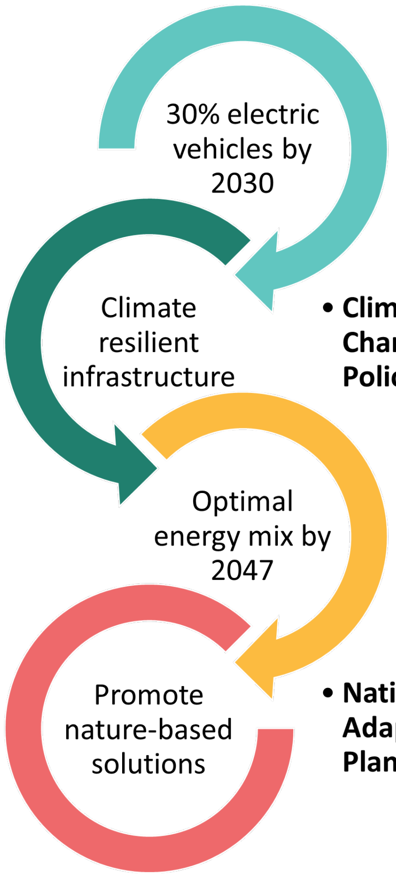
Afghanistan
Kabul
Herat
Tirin Kut
Kandahar
Lashkar Gah
Zabul
Zaranj
Zahedan
Khash
Saravan
Birjand
Quetta
Pakistan
Islamabad
Srinagar
JAMMU AND KASHMIR
LADAKH
Lahore
Multan
Bahawalpur
Larkana
Hyderabad
HIMACHAL PRADESH
CHANDIGARH
PUNJAB
UTTARAKHAND
HARYANA
New Delhi
नई दिल्ली
Bareilly
UTTAR PRADESH
Lucknow
Kanpur
Jaipur
RAJASTHAN
Jodhpur
Ajmer
Jaisalmer
Mount Abu
Udaipur
Kota
Gwalior
Prayagraj
Varanasi
Ayodhya
Gorakhpur
Patna
BIHAR
Darbhanga
Gaya
Nepal
Kathmandu
Hotan Prefecture

Integrating Renewable Energy in Pakistan's Energy Sector: Policy Assessments and Low-Emissions Scenarios

Joudat Bint Khalil[1], Talha Manzoor[1], Muhammad Awais[2,3] Abubakr Muhammad[1]

[1]Centre of Water Informatics and Technology, Lahore University of Management Sciences (WIT, LUMS) [2]International Institute of Applied Systems Analysis [3]University of Victoria

Mitigation Policy Objectives

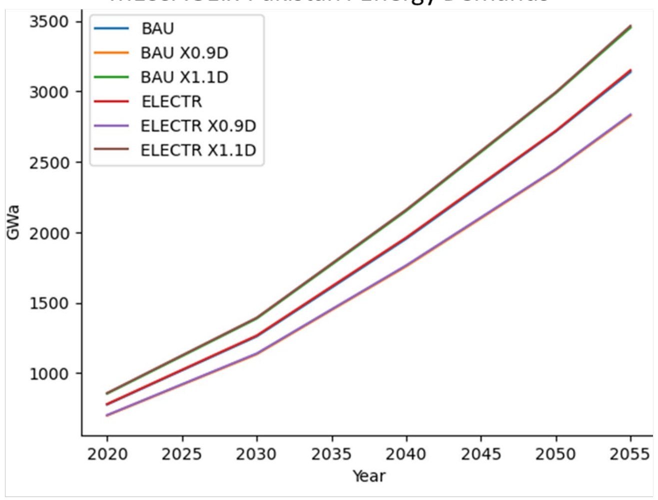


- **NDCs 2021**
- **Climate Change Policy 2021**
- **IGCEP Plan 2047**
- **National Adaptation Plan 2023**

Scenario Design

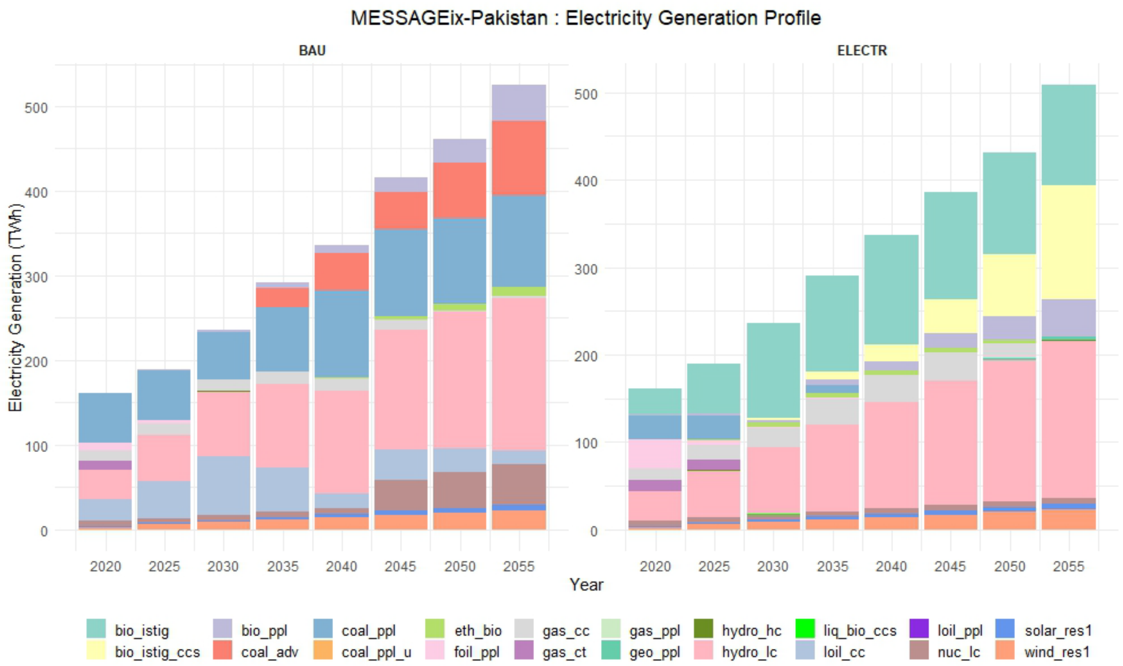
1. Baseline – BAU (Business as usual, 30% Renewable in 2020)
2. Policy Scenario - ELECTR (Rapid Integration of Renewable resources in energy mix)

MESSAGEix-Pakistan : Energy Demands



Demand sensitivity analysis to explore the impact of ±10% demand variations for both scenarios

Insights



- Solution to lower energy sector emissions is integration of renewable resources, irrespective of the demands
- As demand increases, coupled with ambitious integration of renewables, operational and maintenance costs follow suit

Future Plan

- Spatial units – Intersecting Administrative Boundaries with Agro Ecological Zones
- Improvement of hydrological scenarios
- Representation of National Policy and Investment Plan
- Integrating Agriculture and Land Use with Energy Sector
- Scenario Generation for Adaptation and Mitigation
- Micro-behaviors and human processes.