Coupling Agent-based Modeling and Life Cycle Assessment to Analyze Trade-offs in Resilient Energy Transitions

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1. Motivation

The energy sector is undergoing rapid transformation, driving large-scale investments in emerging technologies and pathways. The **siting and co-location** of theses technologies create **synergies** that enhance system efficiency, but also **trade-offs** that reshape the environmental and socioeconomic outcomes and introduce **unintended local risks**.

Figure 1 shows the **integrated framework** from our previous study, developed through a systematic literature review. This framework **bridges silos in management and planning** and illustrates **inter-dependencies** across **natural resources, social and environmental impacts,** and **actionable strategies.**

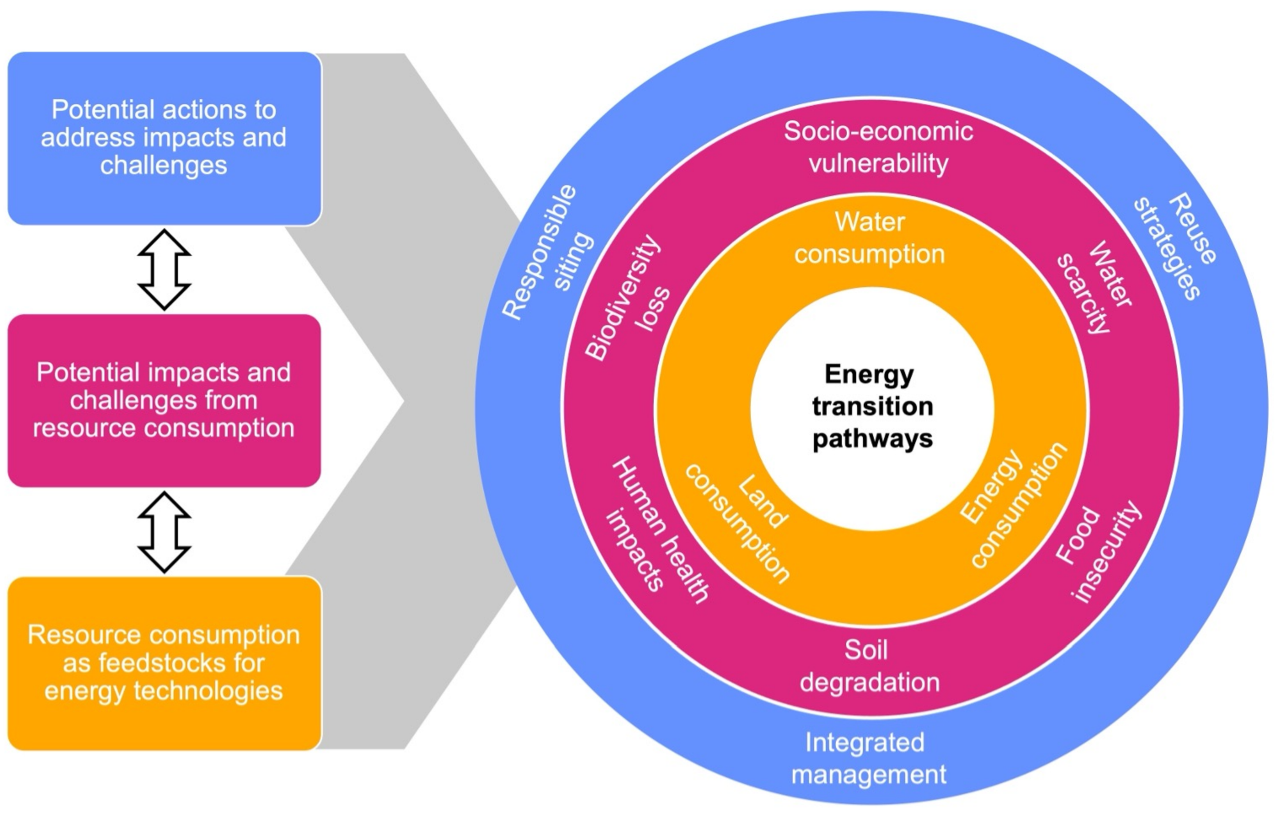


Figure 1: Integrated framework from Zaki et al.

2. Objectives

Can we develop a data-driven model to assess **multifaceted trade-offs** and **local impacts** in deploying multiple emerging **energy transition pathways**?

Translate the conceptual integrated framework to a data-driven simulator

- **Integrate** multi-scale spatial datasets with diverse energy transition pathways to capture cross-sectoral linkages.
- **Represent** interactions among natural resources: water, land, and energy at relevant spatial and temporal scales.
- **Quantify** the environmental and social impacts across pathway portfolios.
- **Facilitate** flexible and scalable scenario analysis through modular model design.

3. Methodology

Figure 2 is a simplified demonstration of the **coupled Agent-based Modeling (ABM) and Life Cycle Assessment (LCA) framework** for simulating the co-locating deployment of emerging energy transition technologies.

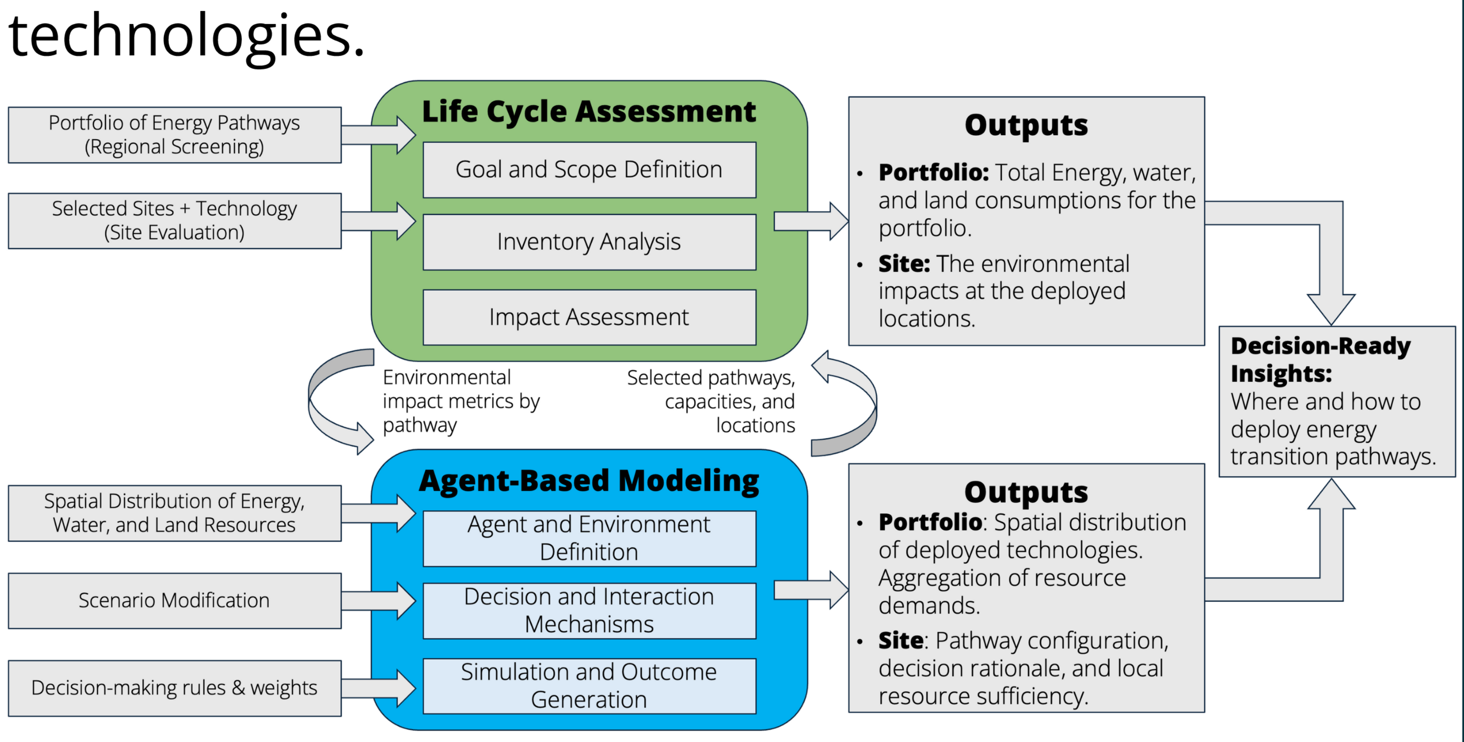
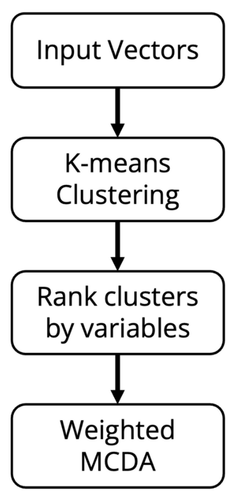


Figure 2: The coupled ABM-LCA framework.

The step-wise flowchart in Figure 3 demonstrates the **data-driven**, **unsupervised learning-based** decision-making process of the agents from multidimensional, multiscalar datasets.



Step 1 – K-means Clustering (unsupervised grouping)

$$\underset{S}{\operatorname{argmin}} \sum_{i=1}^{k} \sum_{x \in S_i} \|x - \mu_i\|^2$$

where, μ_i is the mean (centroid) of points in S_i:

$$\mu_i = \frac{1}{|S_i|} \sum_{x \in S_i} x$$

Step 2 – Ranking Centroids (based on the given order for the feature vector)

$$R_s = \operatorname{argsort}(S_i)$$

Step 3 – Weighted Multi-Criteria Decision Analysis (MCDA)

$$R^{water} = \sum_{c \in C} w_c \cdot R_{s,c}, \text{ where C is the category of water variables}$$

Figure 3: Step-wise flowchart of the agent's decision rationale.

The ABM-LCA model is applied in **Southern California**, where energy transitions face resource limits and socioal and environmental pressures.

4. Results

Table 1 summarizes the portfolio of energy transition pathways used in the Southern California case study. Figure 4 presents the system-level impact assessment across water, land, and energy dimensions. Figure 5 maps site-level hotspots driven by resource-intensive energy transition pathways and co-located siting to reveal synergies and trade-offs.

Pathway	Capacity	Unit
H_2 production by solar	350	MW
H_2 production by wind	300	MW
Ag. and Fo. residues – direct combustion	70	MW
Animal waste – anaerobic digestion	10	MW
Municipal solid waste – landfill gas	300	MW
Municipal solid waste – anaerobic digestion	150	MW
Municipal solid waste – direct combustion	100	MW
Geothermal	450	MW
Direct Lithium Extraction	125,000	Tonne
Direct Air Capture	10,000	Tonne

Table 1: Pathway portfolio.

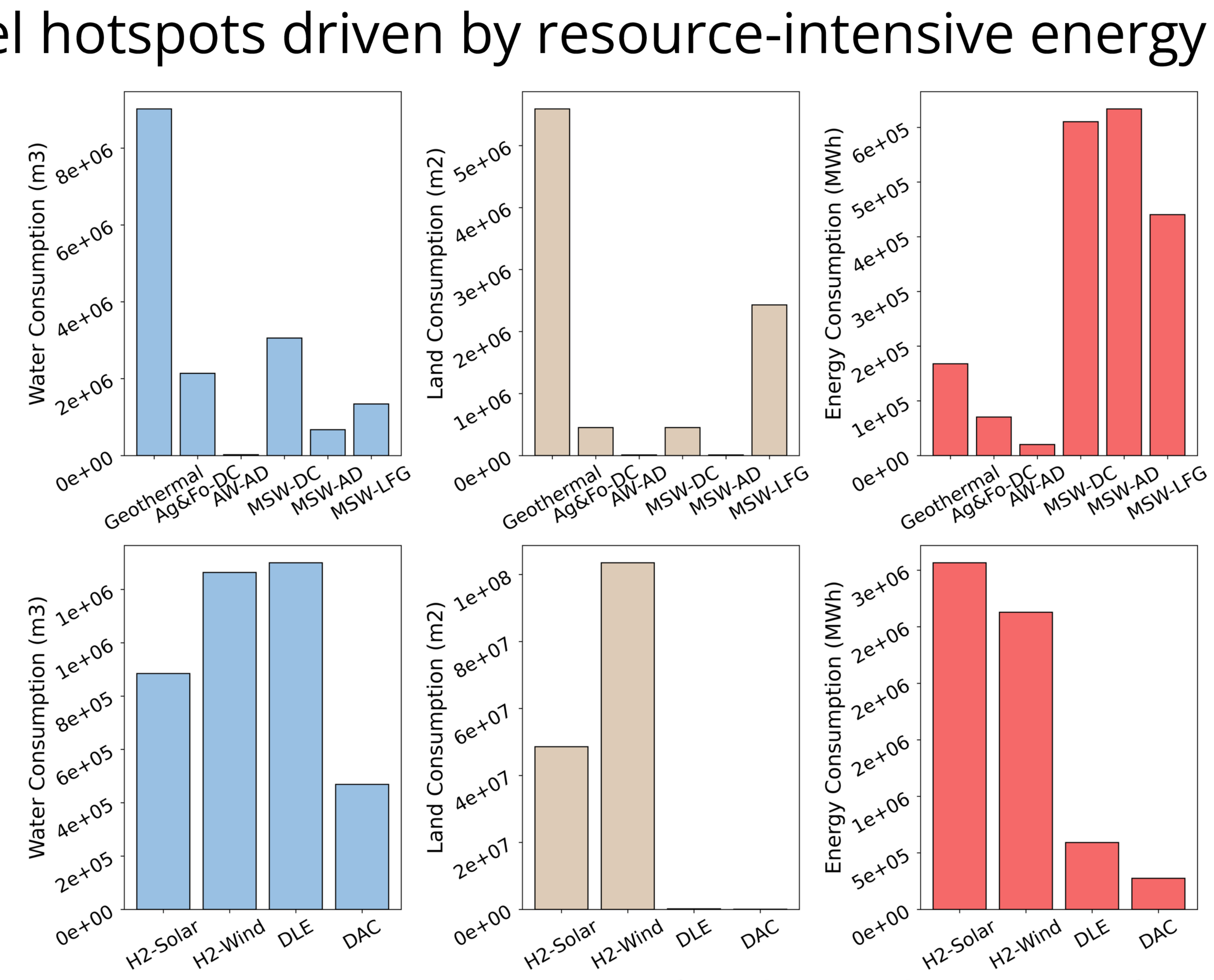


Figure 4: Impact assessment for the pathway portfolio.

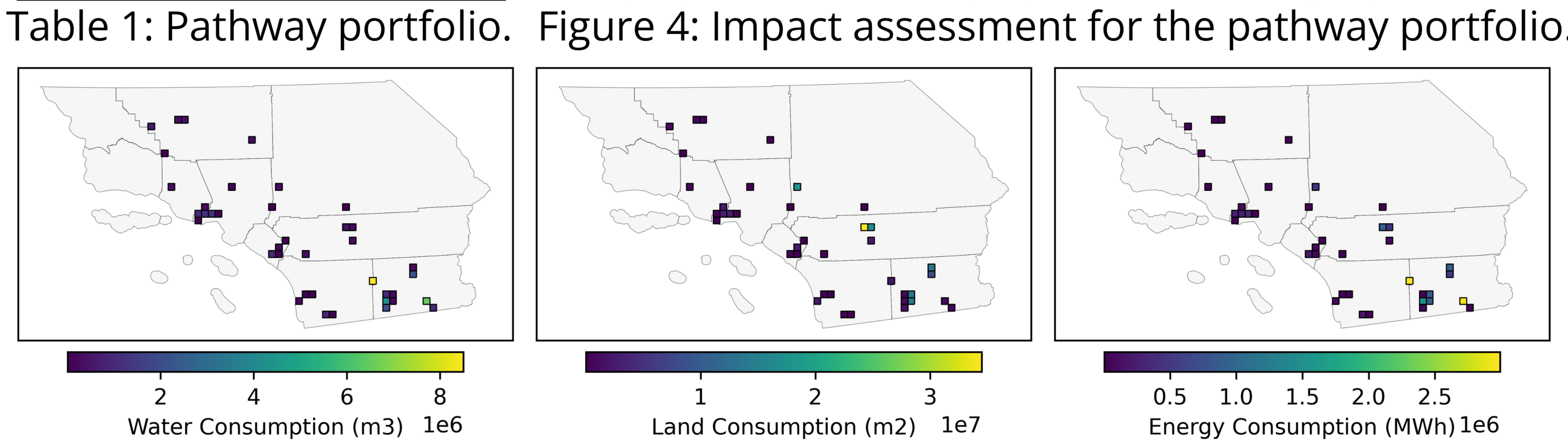


Figure 5: Impact assessment of co-located deployment at the spatial scale.

5. Takeaway & Ackowledgement

We developed the first coupled ABM-LCA model to simulate and assess a portfolio of energy transition pathways at the spatial scale, capturing and comparing multi-pathway, multi-impact, multi-resource, and dynamic interactions.

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