# *THE WATER-ENERGY-MINERAL-LAND NEXUS: INTERLINKED GLOBAL MODELS OF LCIA AND IAM APPLICABLE TO THIS CENTURY*

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## Overview

The current study addresses which resources and interlinkages are relatively impactful to meet the 2-degree Celsius (DC) target in the fully coupled resource nexus, views from material scarcity, among the five resources (water, energy, mineral, food, and land). We developed an interlinked global model of dynamic lifecycle impact assessment (LCIA) and integrated assessment models (IAMs) to address the nexus. We extended the previous version of our IAM to include the impacts of water shortage by the LCIA model, LIME3. The TIAM-FR water model is referred to for the extension. Results show that the carbon budget, the first hidden resource, triggers, and changes significantly on land and energy. Energy induced impacts on minerals, and propagates to water, whereas land to food, and to water. Human, another hidden resource, was given the largest impacts from energy (via local air pollution, climate damage), followed by malnutrition from food, then diarrhea from water.

## Methods

The global scale impacts of water shortage are based on the lifecycle impact assessment method based on endpoint modeling (LIME), version 3. LIME3 enables environmental impacts to be compared among 193 countries and aggregated on a global scale. These include global warming, air pollution, photochemical ozone creation, water, fossil fuel, mineral resources, and forest resources tied to land use (those underlined are included in our previous version of IAM). The previous version comprises three resource balance models (energy, mineral, and land) and a simplified climate model.

We extended the previous IAM to include the impacts of water shortage. The TIMES-FR water model is referred to for the extension. The TIMES-FR water model explicitly treats (1) energy requirements for various water demands in water technologies that bridge the demand and supply of water and (2) water requirements for energy technologies, such as cooling power systems and oil operations. Similar to the way the TIMES-FR model did, we prepared (1) water requirements from models of energy, mineral, and land in our IAM for water demands of industries and agricultural sectors in addition to municipal water demand and (2) energy requirements in water supply systems, specifically power supply from the energy model inside our IAM for pumping, water desalination, purification for potable water, and recycled water treatment.

LIME3 treats water shortage in water demand sectors of agriculture and municipal. Therefore, in our model development, an imbalance between the demand and supply of these two sectors is allowed, whereas the industry water demands inside the energy model and the mineral balance model are fully balanced. LIME3 employs so-called an impact-pathway approach, hence channels from the demand shortages are predetermined. The demand shortages of potable water and agricultural water are impacts of diarrhea and malnutrition, respectively. The physical impacts on human health are monetized by using marginal willingness to pay, hence, the monetized value of the impacts as external environmental costs can be fed back to a macroeconomy model or a total systems cost. The total systems cost consists of the production of resources, land use and land-use changes, inter-regional transportation, energy conversion (power, liquid fuels, gas), utility cost of water supply, production of materials, final demand, wood products, disposal of used products, and materials recycling. Identical to the TIMES-FR water model, investment costs of water supply systems (i.e., cost of water infrastructure) are excluded. Through the feedback, the revised IAM consistently generates demand and supply of the three sectors of water, and energy including utility consumption of water supply, mineral, and land resources by the least cost mechanism.

## Results

Meeting the 2DC target, when compared with those levels under BAU (business-as-usual), leads to the expansion of forest land for carbon sequestration, in addition to the significant reductions of fossil fuel combustions in the energy sector whereas the expansion of renewable energies and fossil-energy carbon capture and storage. Regarding changes in water volume, agriculture-related water dominates the changes from BAU to 2DC due to the expansion of forest land, whereas changes in industry water use are minor. The expansion of forest land via reducing grassland causes a dramatic increase in the external costs of biodiversity impacts from BAU to 2DC especially in the first half-century, whereas in the latter half of the century, energy-related environmental costs (local air pollution is the biggest, followed by climate change) dominate the reductions of the environmental cost (i.e., increased benefit). The external cost of water shortages in human health (mostly malnutrition) is relatively minor. Moreover, meeting the 2DC target leads to the expansion of renewable energies, resulting in an enormous increase in iron and copper usage in the technologies.

## Conclusions

We clarified that the carbon budget, which does not appear in the usual resource nexus illustrations, is a "scarce" resource. Causal chains start from the carbon budget resource to reach land and energy resources. Each causal chain from land and energy arrives not just food but bio-resources (biodiversity) and minerals, respectively. The causal chain to water resources from food causes the biggest changes in water, whereas chains from energy and minerals are very minor. Finally, our analysis based on the lifecycle impact assessments clarifies another hidden resource, which is human resources. Malnutrition from food resources, diarrhea from water resources, and impacts from energy (via local air pollution and climate change) are the three causal chains to human resources. The biggest chain measured by the external costs is the energy, followed by water. Nexus study literature, fully or inclusively addressing representative resources and interlinkages, seems less thin than most of the literature addressing partially. We believe our modeling approach from material scarcity views and findings can contribute to resource nexus studies.