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pathways: life cycle assessment of energy transition scenarios

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Summary

`pathways` is a Python package that conducts Life Cycle Assessment (LCA) to evaluate the environmental impacts of products, sectors, or transition scenarios over time. Unlike most energy (ESM) or integrated assessment models (IAM), `pathways` offers a clearer view on impacts caused by a scenario by considering supply chain relations between producers and consumers, thereby addressing direct and indirect emissions. Unlike the reported emissions in ESM and IAM scenarios, which focus primarily on operation, `pathways` allows reporting the environmental impacts of infrastructure build-up and decommissioning. Finally, scenarios can be characterized across a wide range of indicators which are usually not included in ESM or IAM: land use, water consumption, toxicity impacts, etc.

Statement of need

Most IAMs and ESMs project cost- or utility-optimized future scenarios within specified greenhouse gas emissions trajectories, outlining changes needed in regional energy mixes and means of transport for global warming mitigation (Riahi et al., 2017). Prospective Life Cycle Assessment (pLCA) is crucial for evaluating the environmental performance of existing and emerging production systems, with a growing body of literature in scenario-based pLCA for emerging technologies (Bisinella et al., 2021).

Extending present-day life-cycle inventories into the future using IAM outputs, initially explored by Mendoza Beltran et al. (2018) and formalized by the Python library `premise` (Sacchi et al., 2022), forms the methodological basis for pLCA. Efforts in pLCA focus on improving forecasting accuracy. Performing system-wide LCAs with adjusted life cycle inventories at each time step has potential to enhance sustainability assessments, broadening focus beyond greenhouse gas emissions to include broader environmental impacts like land use, water consumption, and toxicity, addressing both direct and indirect emissions. However, system-wide LCA remains challenging due to computational costs and methodological complexities, such as defining functional units based on IAM outputs and resolving double-counting issues (Vandepaer et al., 2020; Volkart et al., 2018).

Several studies characterize energy scenarios with LCA, including Gibon et al. (2015), Rauner & Budzinski (2017) and Pehl et al. (2017), who quantified ESM or IAM scenario outputs using a hybrid-LCA framework. There is also the work of Xu et al. (2020), who developed the ambitious EAFESA framework aiming for bidirectional coupling between ESM and LCA. Yet, these studies focused on specific sectors or technologies and have not yet generalized to broader scenarios and indicators, nor have they made their implementations widely available.

Beyond conventional pLCA approaches, several tools and frameworks have been developed that leverage LCA data to support further analysis, often through automation and integration with broader modeling frameworks. For example, the ODYM-RECC framework integrates LCA data to assess resource efficiency within climate mitigation scenarios, providing insights on material demand and supply chain impacts (Pauliuk et al., 2021). Similarly, the Mat-dp tool, when supplied with suitable input data, can be used to calculate materials needed and estimate environmental impacts of transition scenarios (Cervantes Barron & Cullen, 2022, 2024). However, because these tools depend on exogeneous input data, they are not designed to systematically consider the time-dependent technology mixes influencing the production system. This limits their ability to endogenously and dynamically assess evolving environmental impacts and material demand, restricting consistency with the scenario assessed.

To address these challenges, the open-source library pathways utilizes the LCA framework brightway (Mutel, 2017) to systematically evaluate environmental impacts of energy transition scenarios. pathways works with data packages containing LCA matrices adjusted to each time step of the ESM/IAM scenario, providing detailed and transparent insights into scenario environmental impacts. pathways works particularly well with data packages produced by premise, but can be used with any ESM/IAM scenarios and LCA databases. Using LCA matrices which have been modified to reflect the scenario's time-dependent technology mixes ensures a consistent and coherent characterization of the scenario.

Description

pathways reads a data package containing scenario data, mapping information, and LCA matrices. The data package should be a zip file containing the following files:

- datapackage.json: a JSON file describing the contents of the data package
- a mapping folder containing a mapping.yaml file that describes the mapping between the IAM scenario variables and the LCA datasets
- an inventories folder containing the LCA matrices as CSV files for each time step
- a scenario_data folder containing the scenario data as CSV files

pathways reads the scenario data files (1 in Figure 1), and iterates, for each time step and region, through technologies with a non-null production volume. For each technology, pathways retrieves the corresponding LCI dataset by looking it up in the mapping file (2 in Figure 1). The lookup indicates pathways which LCA matrices to fetch from the data package (3 in Figure 1). The LCA matrices are loaded in bw2calc (the LCA calculation module of brightway) and multiplied by the production volume (see 4 in Figure 1). The results are aggregated and saved in a dataframe, where impacts are broken down per technology, region, time step, geographical origin of impact, life-cycle stage and impact assessment method (6 in Figure 1).

Some post-processing is done on the inventory matrices, including managing double counting. Double counting occurs when resource demands are counted multiple times across interconnected system components, inflating environmental impacts. This issue is particularly relevant when the reference scenario (e.g., from an IAM) already accounts for total regional demand, such as electricity or transport. For example, if electricity and steel production are interdependent, evaluating total electricity demand as defined by the scenario may lead to overlap: electricity requires steel, and steel production, in turn, requires additional electricity beyond the initial total. This overlap results in duplicative demand estimates.

To address this, the original LCI database is adjusted by zeroing out all regional energy inputs that the energy system model accounts for and might demand during the system's life cycle, following the same workflow presented in Volkart et al. (2018) (see 5 in Figure 1). Practitioners are required to selectively cancel out overlapping activities already accounted for by the scenario. We use a modular approach in this adjustment process, where practitioners, based on their understanding of the model generating the scenario, can select specific activity categories (e.g., electricity, heat, or specific product inputs) to exclude. For instance, if the IAM models regional electricity generation, the corresponding electricity inputs in the LCA system for upstream processes are removed to prevent double counting. Returning to the electricity-steel example, this means the practitioner would exclude electricity inputs for steel production within the LCA, as the scenario's total electricity demand already covers this requirement.

This process is implemented in the `remove_double_accounting` function, which modifies the technosphere matrix to remove redundant entries. The function identifies flagged products for removal, locates the associated rows, and zeroes out the corresponding positions taking any specified exceptions. For instance, in the electricity-steel example, the function would find the row corresponding to regional electricity and cancel out the input in the column associated with steel production, effectively preventing double counting of electricity demand. This modular approach enhances transparency and traceability, making it easier to document and track which system components are modified, ensuring consistency between the scenario outputs and the LCA.

Finally, Global Sensitivity Analysis (GSA) can be performed on the results. Currently, `pathways` supports the use of the `SALib` library for GSA (Herman & Usher, 2017; Iwanaga et al., 2022), notably the Delta Moment-Independent Measure (DMIM) method (Borgonovo, 2007), to rank the influence of the database exchanges on the results.

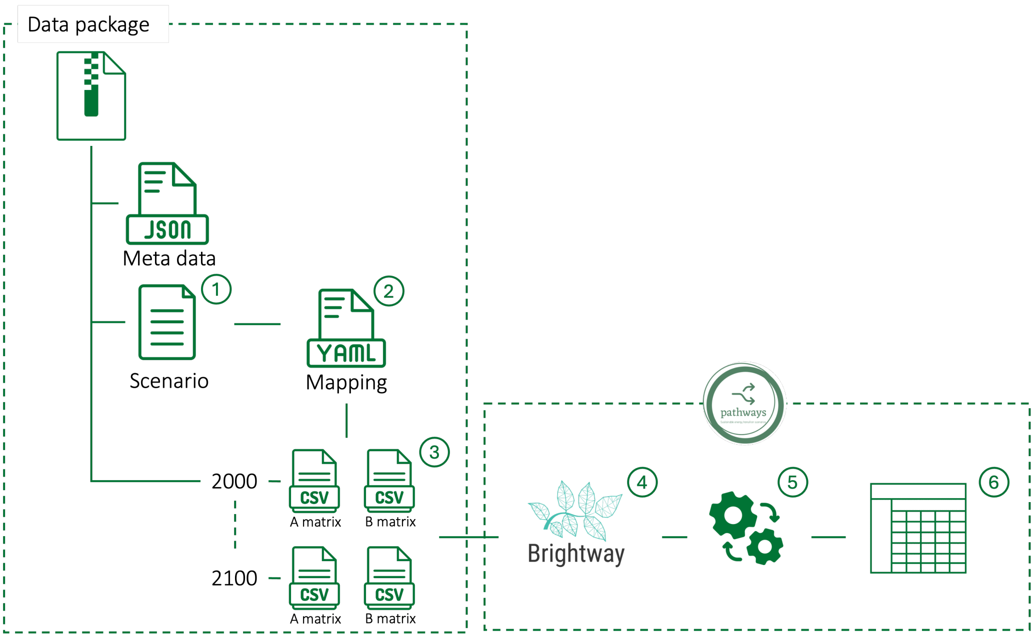

Figure 1: `pathways` workflow: from data package to impact assessment.

A detailed example notebook is available for using `pathways` with a sample data package.

Impact

By systematically updating and integrating LCA matrices over time, `pathways` improves the accuracy and relevance of environmental impact assessments for transition scenarios. This tool fosters greater alignment between LCAs and ESM/IAM outputs, enhancing the consistency and reliability of environmental assessments across different modelling platforms.

Additionally, `pathways` offers a detailed and structured workflow that enables IAM modellers to incorporate LCA into their analyses. This opens new avenues for these modellers to enhance the environmental dimension of their work.

Designed to be both reproducible and transparent, `pathways` facilitates collaboration and verification within the scientific community. This approach ensures that improvements in environmental impact assessments are accessible and beneficial to a broader range of stakeholders.

Conclusion

`pathways` is a tool that evaluates the environmental impacts of transition scenarios over time using time-adjusted and scenario-based LCA matrices. This approach allows for characterizing the environmental impacts of a scenario across a wide range of indicators, including land use, water consumption, toxicity impacts, etc. It also allows to attribute supply chain emissions to the final energy carriers, thus providing a more detailed and transparent view of the environmental impacts of a scenario.

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