26th International Congress on Modelling and Simulation, Adelaide, SA, Australia, 30 Nov–4 Dec 2025
mssanz.org.au/modsim2025

A system-wide Energy Return on Investment (EROI) approach to Australia's renewables transition

B Lloyd-Hurwitz [a], T Khandoker[b] and L Reedman [b]

[a] *Australian National University, Canberra*
[b] *Commonwealth Scientific and Industrial Research Organisation (CSIRO)*
Email: benlloydhurwitz@gmail.com

Abstract: This study presents a national, systemwide assessment of Australia's Energy Return on Investment (EROI)—a key measure of the net energy available to sustain economic and social systems. As energy systems transition from fossil fuels to renewables, it is essential to understand whether they provide sufficient net energy, that is, the energy remaining once the energy consumed during extraction, transportation, and manufacturing for the grid is accounted for.

Existing EROI literature suffers from two key gaps: a lack of country-specific, systemwide analysis and insufficient consideration of energy storage, trade, and capital goods. These limitations are particularly important in the Australian context, where strong rooftop solar penetration, substantial fossil fuel exports, and import-reliance for manufactured goods create a distinct energy profile. To address these gaps, this research develops a transparent methodology to calculate Australia's EROI at the final energy stage, incorporating embodied energy and storage losses. The analysis is designed to align with a biophysical Stock-Flow Consistent (SFC) macroeconomic model under development, supporting more comprehensive energy-economic policy analysis.

The study adopts both input-output and process-based approaches to calculating EROI at a national, systemwide level. For the input-output calculation, technology-level (e.g. solar photovoltaic (PV) arrays, coal power plants) transmission loss data was added to the Australian Energy Update, a national physical energy flow dataset. These transmission losses were sourced from the Australian Energy Market Operator (AEMO) through published marginal loss factors (MLFs). For the process-based calculation, over 100 existing technology-level calculations were harmonised and weighted by recency and location to create EROI estimates for each technology (including storage such as batteries). Using a methodology pioneered by Sahin et al. (2024), these technology-level EROIs were then combined to create a systemwide EROI, which is calculated both for the current Australian grid and under future AEMO scenarios.

The results show that Australia's national EROI has remained stable (between 5-15 for both approaches) over the past decade and is expected to remain so throughout the transition to renewables. This is due to the comparable EROIs of fossil fuel and renewable technologies, even when accounting for storage and system losses. The findings suggest that Australia's renewable energy transition can maintain sufficient net energy to support broader economic and societal needs.

Current models of the economy and the energy grid (e.g. AusTIMES) have utilised monetary metrics, such as the Levelised Cost of Electricity (LCOE), to explore future transition scenarios. This study is the first step in including physical and systemwide metrics, such as EROI, in these models. Alongside monetary metrics, physical metrics can highlight key feedback between the environment, the energy grid, and the economy, ensuring that economic models are not divorced from the physical systems that underlie economic systems. The framework developed here offers a replicable, policy-relevant tool for assessing energy transitions and informing long-term sustainability planning.

Keywords: *Energy return on investment, system boundaries, life cycle assessments, green transition, ecological macroeconomics*

1. INTRODUCTION

Energy Return on (energy) Investment (EROI) is the ratio of the energy output from a system to the energy required to produce this energy (the "energy investment"). As an equation, we have:

$$\text{EROI} = \frac{\text{Energy Output}}{\text{Energy Investments}} \quad (1)$$

For example, a gas boiler produces heat as its energy output, but requires energy investments to extract, refine, and transport the gas. The raw energy in the unrefined gas is not counted as an energy investment, thus net energy is produced when the EROI exceeds 1. However, this deceptively simple equation conceals many methodological difficulties.

EROI is central to ecological macroeconomics and biophysical economics, as it reflects the physical constraints underpinning economic activity (Hafner et al., 2020). As Smil (2017) argues, the harnessing of energy has been a key driver of human progress. In this context, EROI serves as an indicator of the energy system's capacity to consistently support economic and social functions.

While the concept of a "minimum EROI" necessary for society to function is problematic and poorly quantified, estimates are usually around 3-10 (Fizaine and Court, 2016). Historically, declining EROI has been linked to economic shocks, like the 1970s oil crises. Today, as nations shift from fossil fuels to renewable sources, EROI has re-emerged as a critical metric. Delannoy et al. (2024, pp. 11–12) argue that "net energy is critical for the assessment of equitable and feasible transition scenarios." Moreover, EROI correlates with the emissions intensity of the energy sector: if electricity requires more energy to produce per unit of output, it likely produces greater emissions (although Sahin et al. (2024a) find this is not universally true). Thus, a comparison of EROIs can inform decisions about the energy mix.

1.1. Methodological Challenges and the Need for Consistency

Evaluating the viability of energy systems—especially during a renewable transition—requires a consistent approach to measuring EROI. The EROI literature has previously suffered from methodological inconsistencies, particularly in defining system boundaries. Studies differ in how they account for energy inputs and outputs, which leads to conflicting results. These inconsistencies arise along three dimensions:

- Product system boundaries (e.g. primary, final, and useful energy; see next paragraph)
- Geographic boundaries (e.g. site-specific, national, global)
- Temporal boundaries (e.g. annual flows vs. lifecycle analysis)

These variations hinder the comparability of studies and limit the applicability of EROI in policymaking (Murphy et al., 2022). **Primary EROI**, often applied to fossil fuels, measures energy at the point of extraction but ignores downstream processing and distribution. This presents an unfair comparison with renewables, which do not require processing. At the other extreme, **useful EROI** measures the energy after conversion in an end-use device, such as the lumens of light provided by a lamp. While recent studies have estimated useful EROI (e.g. Aramendia et al. 2024), its measurement is too resource-intensive for this report. Instead, this report adopts **final EROI**, which measures energy at the point of use (e.g. the fuel pump or the socket).

Further complexity arises in accounting for energy storage, which is vital for variable renewable energy (VRE) systems. This study includes energy storage in the national EROI calculation, addressing a growing methodological gap. For the temporal boundary, lifecycle energy investment figures are apportioned to each year of use to give annual EROI estimates.

1.2. Analytical Framework and Approaches

While energy output is relatively easy to calculate, energy invested is more difficult. For each component of the energy system (e.g. solar panels, coal power plants), we need to model the energy invested across their entire life cycle. This is called a life cycle inventory (LCI). For conducting LCIs, there are both top-down **input-output (IO) models**, and bottom-up **process-based analyses** (Brand-Correa et al., 2017), as well as hybrid approaches which lie on a spectrum between these (Crawford et al., 2018)

Input-output models track flows across an economy, usually at a national level. **Monetary IO** models convert economic flows from aggregate statistical tables (e.g. purchases between sectors) into energy values using an estimate for energy intensity. While comprehensive, these models may fail to conserve energy and often exclude embodied energy in capital goods (Aramendia et al., 2022). **Physical IO** models address these issues by tracking energy flows directly in physical units (Heun et al. 2018). They include imports/exports and energy gained from and lost to the environment, but like Monetary IO models, can lack the resolution to distinguish between different types of energy generation (e.g. solar vs wind). Nevertheless, this project conducts a physical IO analysis of Australia's EROI.

Process-based LCIs, on the other hand, examine the supply chain of energy technologies from the bottom up. Recent innovations, such as those proposed by Sahin et al. (2024), allocate energy investments across the life of an asset, enabling consistent annual EROI calculations at the system level. However, at some point the supply chain analysis must stop, introducing potential inaccuracies. Process-based LCIs are also time intensive to calculate, especially at a national/global level with multiple technologies in the electricity mix. This project adopts such a lifecycle-based approach by synthesising existing studies.

Hybrid methods aim to combine the strengths of both approaches (Crawford et al. 2018). While this project did not have the time to consider these methods in detail, it did adopt some hybrid elements in its physical IO.

1.3. Review of Related Studies and Novel Contributions

Global EROI studies have developed significantly in the last decade. Harmonised metrics and improved methods now enable consistent comparisons across energy technologies and regions. Recent findings indicate that renewables—particularly solar photovoltaic (PV) and wind—often exhibit higher final EROIs than fossil fuels, even accounting for storage (Delannoy et al., 2024; Murphy et al., 2022).

In Australia, however, dedicated national-level EROI studies remain limited. Palmer (2017) used a monetary IO method to estimate a high gross systemwide EROI (approx. 40) but lacked detail on solar PV and the embodied energy in imported goods (like wind turbines), and only reported data for 2013. Trainer (2018) modelled a 100% renewable scenario but employed a simplified and ad-hoc method. Several other studies (e.g. Crawford et al., 2022) address embodied energy or hybrid LCI approaches, but none provide a comprehensive national EROI integrating both fossil and renewable systems under dynamic conditions.

This study responds to two key gaps in the existing literature. First, there is a lack of national-scale, dynamic EROI analysis for Australia. Most existing studies focus either on specific technologies or global averages, overlooking the country-specific energy dynamics that shape national policy decisions. Given Australia's distinct energy profile—characterised by high rooftop solar penetration, fossil fuel exports, and reliance on imported manufactured goods—a dedicated national analysis is essential. Second, current Australian studies insufficiently account for systemwide factors such as energy storage, capital goods, and trade flows. These elements are critical in accurately assessing the evolving EROI of a transitioning energy system but have been excluded or treated simplistically in prior work.

To address these gaps, this study develops a consistent and transparent methodology for calculating Australia's national-level EROI at the final energy stage, incorporating storage systems and embodied energy inputs. It captures changes in EROI over time, reflecting technological advances and resource constraints. The approach is designed to be integrated with a national biophysical Stock-Flow Consistent (SFC) macroeconomic model currently under development, enabling an integrated assessment of how net energy availability influences economic stability and policy design (Jackson and Jackson, 2025). By adopting a national perspective, the study ensures systemwide features such as trade, transmission, and storage are explicitly considered. The resulting framework will not only improve the robustness of Australian energy policy analysis but also offers a replicable and policy-relevant tool for other countries navigating similar energy transitions.

The rest of the paper is organised as follows: The next section outlines the methods and data used in this study, section 3 presents the key findings and reflects on the study's limitations, and section 4 gives our conclusions.

2. METHODOLOGY AND DATA

This project applies both IO and Process-Based approaches to estimate Australia's national-level EROI.

2.1. Data Availability

This study draws on a combination of international and national data sources to estimate Australia's national-level EROI. Key international input-output datasets include the IEA's (2024) proprietary global energy balances dataset, EXIOBASE 3 (freely accessible but limited to 2011), and Australia-specific data from the Industrial Ecology Virtual Laboratory (IELab). For process-based data, Ecoinvent offers detailed life cycle inventories but was not directly accessible for this study; we obtained some insights through published studies (e.g. Sahin et al., 2024a). AusLCI, Australia's open-source LCI database, was explored but proved challenging to apply due to an outdated interface (Australian Life Cycle Assessment Society, n.d.). At the national level, the Australian Bureau of Statistics (ABS) and the Department of Climate Change, Energy, the Environment and Water (DCCEEW) both publish energy datasets. This project uses DCCEEW's (2024) Australian Energy Update (AEU), which applies an activity-based accounting perspective that is more suitable for EROI calculations than the ABS's industry-based approach. However, the AEU lacks data on embodied energy, storage, and technological disaggregation, requiring supplementary estimates and methodological adjustments.

2.2. Physical Input-Output Approach and Marginal Loss Factors

The physical IO approach used AEU physical energy flow data, however, it required significant pre-processing due to inconsistencies in fuel naming. Some critical data, such as fuel-specific stock changes and discrepancies, are only available in aggregated form, and energy import/export figures are split across different tables.

A major limitation is the lack of technological disaggregation within the electricity sector. To overcome this, electricity generation data from the Australian Energy Market Operator (AEMO) was used to distinguish between sources such as coal, gas, wind, hydroelectricity, and solar PV. Energy losses during transmission were estimated using Marginal Loss Factors (MLFs), which AEMO publishes annually to adjust pricing based on location-specific transmission losses.

MLFs were aggregated by technology to estimate transmission losses per source, informing the construction of an augmented input-output matrix. We introduced disaggregated electricity sectors (e.g. "Electricity – Black Coal") in this matrix to enable more detailed EROI estimation. Grid-level electrical losses reported in the AEU were then allocated to these disaggregated sectors based on AEMO's site-level data.

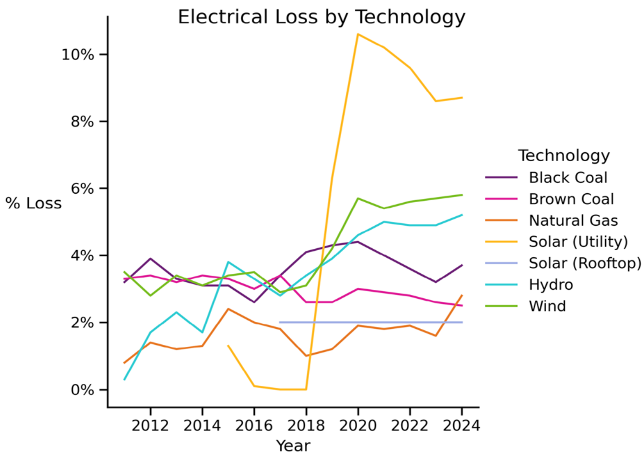

Figure 1 Electrical losses per technology, calculated from AEMO transmission data

However, several limitations remain. MLFs represent marginal, not average, losses, and applying them to entire generation profiles introduces inaccuracies—particularly for large generators like coal plants. Although using average loss factors would be more appropriate, these are not publicly available. Moreover, attributing losses to specific technologies may be conceptually misleading, as transmission infrastructure serves the grid as a whole, not individual sources.

Despite these limitations, this approach enhances the resolution of national energy data and provides a more nuanced estimate of systemwide EROI. Final EROI values were calculated using established methods (Aramendia et al., 2024; Brand-Correa et al., 2017), producing annual supply-use tables with disaggregated electricity technologies.

The total losses for each technology were calculated for each generator, as shown in Figure 1.

2.3. Process-Based Approach

Due to limited time and expertise, this project did not undertake an original process-based life cycle analysis. Instead, it relied on peer-reviewed meta-analyses, including Murphy et al. (2022), Slameršak et al. (2022), and (for wind specifically), Carbajales-Dale (2023). Relevant studies were compiled and further sources were added for completeness.

To ensure consistency, all values were harmonised to reflect final EROI. For example, Murphy et al.'s (2022) data—reported as primary energy equivalents—were adjusted using a standard grid efficiency factor of 0.3, though this method has known limitations. Some studies reported net EROI, which were converted to gross EROI using the following identity:

$$\text{Net EROI} = \frac{\text{Energy Output} - \text{Energy Investments}}{\text{Energy Investments}} = \frac{\text{Energy Output}}{\text{Energy Investments}} - 1 = \text{Gross EROI} - 1 \quad (2)$$

Studies with known errors or implausibly low EROI values (e.g. <1) were excluded. A weighted average was used to aggregate values, giving preference to recent and Australia-specific datapoints (although these were comparable to international datapoints in general).

This harmonised literature was used to estimate **systemwide final EROI** following Sahin et al. (2024):

$$\mathrm{EROI}_{\mathrm{sys},y} = \frac{\text{Energy Supply (minus losses)}}{\sum_g \frac{Gen_{g,y}}{\mathrm{EROI}_g} + \sum_s \frac{\mathrm{Storage}_{s,y}}{\mathrm{ESOI}_s}} \tag{3}$$

To calculate the energy investments (the denominator), the formula combines technology-level EROIs from both generation (g) and storage (s), for a given year (y). As EROI = output/input, the input for each technology is the output divided by the EROI (or, in the case of storage, the Energy Storage on Invested [ESOI]). This is then summed to give the total energy investments for the entire system, for a given year.

Energy supply data were drawn from AEMO, with losses assumed at 4.5% (AEMO, 2012, p. 7). Generation EROIs were estimated using average literature values for each technology. ESOI values, sourced from Carbajales-Dale et al. (2014), account for storage round-trip efficiency.

Finally, the model was extended to simulate future national EROI under AEMO's 2024 Integrated System Plan (ISP) scenarios: Progressive Change, Step Change, and Green Energy Exports (AEMO 2023).

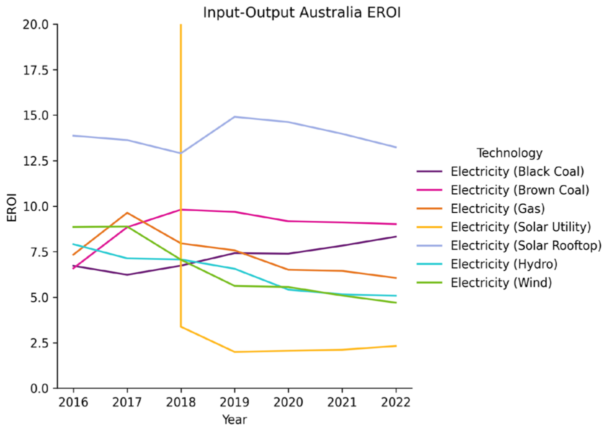

Figure 2 Australia's EROI from the Input-Output Methodology

3. RESULTS AND DISCUSSION

3.1. Input-Output Results

The Input-Output results for electricity are shown in Figure 2. This analysis considers only transmission losses and excludes embodied energy. Solar utility showed an unusually high EROI in 2016–2017 due to initial data artefacts and favourable Marginal Loss Factors, which reversed after 2018. Since then, solar utility has had the lowest EROI (2.5) due to significant transmission losses. In contrast, Solar Rooftop maintains a high EROI as it avoids high-voltage transmission, incurring only minimal distribution losses (2%). EROIs for other technologies—gas, hydro, wind, and coal—range between 5 and 10. While gas, hydro, and wind EROIs have declined over time, coal EROI has remained stable or slightly increased.

3.2. Process-Based Results

Figure 3 summarises EROI values from process-based studies, showing that renewable technologies—especially hydropower—match or exceed fossil fuels in EROI, consistent with Delannoy et al. (2024). For storage, pumped hydro significantly outperforms batteries in ESOI due to its large capacity. Nuclear has a

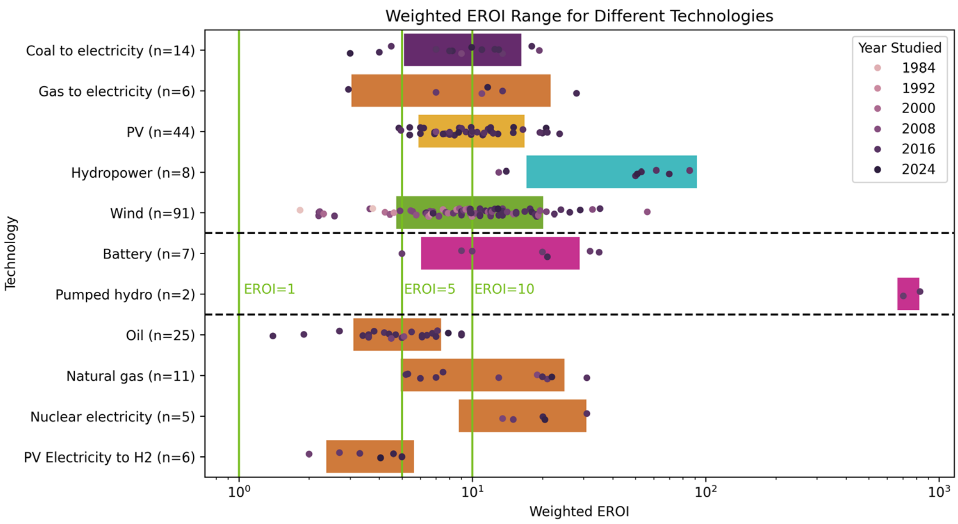

Figure 3 EROIs from the literature, weighted by recency and location

strong EROI, while PV-to-hydrogen remains low. These EROIs roughly align with the IO results, with coal, gas, solar all lying between 5 and 15. However, the process-based approach gives hydropower a significantly higher EROI.

These weighted values were combined with historical generation data and AEMO's Step Change scenario to estimate Australia's system-level EROI (Figure 4). Results show a stable EROI around 10 throughout the energy transition. Similar outcomes are observed under other scenarios, including Green Energy Exports.

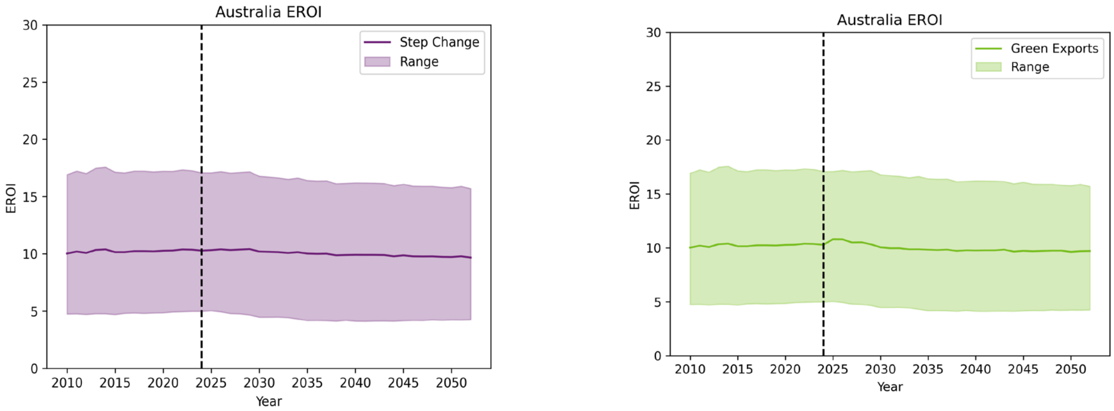

Figure 4 Process-based EROI, under the Step Change and Green Energy Exports scenarios

4. CONCLUSION AND FUTURE WORK

This study addressed longstanding methodological confusion surrounding Energy Return on Investment (EROI) by adopting and adapting recent international advances for the Australian context. Using both input-output and process-based approaches, it offered a transparent, systemwide assessment of Australia's national EROI. The findings suggest Australia's EROI has remained relatively stable over the last decade and is projected to stay within a viable range (5–15) throughout the energy transition. This stability is encouraging, as it exceeds often-cited thresholds of the EROI required to sustain modern economies (typically between 3–10).

Beyond serving as a standalone metric, EROI can support broader energy modelling as a complementary tool to cost metrics like LCOE and as a biophysical constraint within macroeconomic models. However, both approaches to calculating EROI have limitations. Input-output methods enable technology-level disaggregation but struggle to allocate transmission losses and omit embodied energy. In contrast, the process-based method better captures supply chain and storage inputs but relies on international data not always reflective of Australian conditions.

Both methods currently focus on the electricity sector, excluding direct fuel use in transport and industry. Storage modelling is also limited by data constraints, particularly around differentiating between battery and pumped hydro systems.

4.1. Future Work

Future research should incorporate dynamic EROI trends by technology, improve transmission loss modelling, and integrate embodied energy into an IO model. Broadening the analysis beyond electricity will enhance the comprehensiveness of national EROI estimates. Ultimately, this work will inform the integration of EROI into a biophysical Stock-Flow Consistent model for Australia's economy, strengthening energy-economic policy analysis.

ACKNOWLEDGEMENT

Ben Lloyd-Hurwitz expresses sincere gratitude to his supervisor Dr Taj Khandoker, whose enthusiasm for economics and energy systems is unending, and whose guidance greatly supported this project. He also wishes to thank Luke Reedman and James Foster for their assistance, as well as the entire team at CSIRO's Energy Centre in Newcastle. The data and Python scripts used for this study are available from the authors upon reasonable request.

REFERENCES

AEMO (2012) Treatment of loss factors in the national electricity market https://www.aemo.com.au/-/media/Files/Electricity/NEM/Security_and_Reliability/Loss_Factors_and_Regional_Boundaries/2016/Treatment_of_Loss_Factors_in_the_NEM.pdf

AEMO (2023) 2024 ISP Delphi Panel https://aemo.com.au/-/media/files/major-publications/isp/2023/2024-isp-delphi-panel---overview.pdf

Aramendia E, Brockway PE, Taylor PG, Norman JB, Heun MK and Marshall Z (2024) Estimation of useful-stage energy returns on investment for fossil fuels and implications for renewable energy systems. Nat Energy 9, 803–816. https://doi.org/10.1038/s41560-024-01518-6

Australian Life Cycle Assessment Society (n.d.) AusLCI datasets URL https://www.auslci.com.au/index.php/Datasets (accessed 2.28.25).

Brand-Correa LI, Brockway PE, Copeland CL, Foxon, TJ, Owen A and Taylor PG (2017) Developing an Input-Output Based Method to Estimate a National-Level Energy Return on Investment (EROI). Energies (Basel) 10, 534. https://doi.org/10.3390/en10040534

Carbajales-Dale M, Barnhart, CJ and Benson SM (2014) Can we afford storage? A dynamic net energy analysis of renewable electricity generation supported by energy storage. Energy Environ Sci 7, 1538–1544. https://doi.org/10.1039/C3EE42125B

Carbajales-Dale M (2023) Life cycle assessment: a meta-analysis of cumulative energy demand and greenhouse gas emissions for wind energy technologies, in: Letcher TM (Ed.), Wind Energy Engineering (Second Edition). Academic Press, pp. 423–442.

Crawford RH, Bontinck PA, Stephan A, Wiedmann T and Yu M (2018). Hybrid life cycle inventory methods – A review. J Clean Prod 172, 1273–1288. https://doi.org/10.1016/j.jclepro.2017.10.176

Crawford RH, Stephan A and Prideaux F (2022) The EPiC database: Hybrid embodied environmental flow coefficients for construction materials. Resour Conserv Recycl 180, 106058. https://doi.org/10.1016/j.resconrec.2021.106058

DCCEEW (2024) Australian Energy Update https://www.energy.gov.au/publications/australian-energy-update-2024

Delannoy L, Auzanneau M, Andrieu B, Vidal O, Longaretti P-Y, Prados E, Murphy DJ, Bentley RW, Carbajales-Dale M, Raugei M, Höök M, Court V, King CW, Fizaine F, Jacques P, Heun MK, Jackson A, Guay-Boutet C, Aramendia E, Wang J, Boulzec H and Hall CAS (2024) Emerging consensus on net energy paves the way for improved integrated assessment modeling. Energy Environ Sci 17, 11–26. https://doi.org/10.1039/D3EE00772C

Fizaine F and Court V (2016) Energy expenditure, economic growth, and the minimum EROI of society. Energy Policy 95, 172–186. https://doi.org/10.1016/J.ENPOL.2016.04.039

Hafner S, Anger-Kraavi A, Monasterolo I and Jones A (2020) Emergence of New Economics Energy Transition Models: A Review. Ecological Economics. https://doi.org/10.1016/j.ecolecon.2020.106779

Heun MK, Owen A and Brockway PE (2018) A physical supply-use table framework for energy analysis on the energy conversion chain. Appl Energy 226, 1134–1162. https://doi.org/10.1016/j.apenergy.2018.05.109

IEA (2024) World Energy Balances - Data product - IEA [WWW Document]. URL https://www.iea.org/data-and-statistics/data-product/world-energy-balances (accessed 2.28.25).

Jackson A and Jackson T (2025) Macroeconomic, sectoral and financial dynamics in energy transitions: A stock-flow consistent, input-output approach. Ecological Economics 230, 108507. https://doi.org/10.1016/J.ECOLECON.2024.108507

Murphy DJ, Raugei M, Carbajales-Dale M and Estrada BR (2022) Energy Return on Investment of Major Energy Carriers: Review and Harmonization. Sustainability (Switzerland) https://doi.org/10.3390/su14127098

Palmer G (2017) An input-output based net-energy assessment of an electricity supply industry. Energy 141, 1504–1516. https://doi.org/10.1016/j.energy.2017.11.072

Sahin H, Solomon AA, Aghahosseini A and Breyer C (2024) Systemwide energy return on investment in a sustainable transition towards net zero power systems. Nat Commun 15, 208. https://doi.org/10.1038/s41467-023-44232-9

Smil V (2017) Energy and Civilization: A History. Boston: MIT Press.

Trainer T (2018) Estimating the EROI of whole systems for 100% renewable electricity supply capable of dealing with intermittency. Energy Policy 119, 648–653. https://doi.org/10.1016/j.enpol.2018.04.045

