When models outrun politics: Biofuels as a stress test for scenario plausibility

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Perspective

When models outrun politics: Biofuels as a stress test for scenario plausibility

Fredrik Hedenus

Department of Environmental and Energy Sciences, Division of Physical Resource Theory, Chalmers Technical University, Sweden

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ABSTRACT

Long-term energy scenarios often assign a substantial role to biofuels in net-zero pathways, despite decades of policy support and limited evidence of sustained cost reductions or large-scale diffusion. Using biofuels as a critical case, this paper examines a broader problem in scenario construction: the misalignment between modelled technology pathways and socio-technical feasibility. Drawing on innovation theory, learning-curve evidence, and observed patterns of policy support and investment, it argues that biofuels are constrained by a configuration of mutually reinforcing limitations, including feedstock-dominated costs, weak learning dynamics, and permanent policy dependence. These constraints do not form a simple causal chain, but jointly limit the conditions under which large-scale competitiveness could emerge. Despite this, energy system and integrated assessment models often project extensive biofuel deployment under assumptions that abstract from political volatility and investment risk. The paper argues for greater use of empirical plausibility checks to improve the relevance of long-term energy scenarios.

1. Introduction

Four decades of subsidies, mandates, and pilot projects have left biofuels still marginal in global energy supply and remain rarely cost-competitive with fossil fuels [1,2]. Costs remain stubborn and diffusion limited, yet energy system models and integrated assessment models (IAMs) often assign them a role in net-zero strategies [3–5]. The role differs, across published scenarios, biofuel use in 2050 ranges from negligible levels to around 50 EJ [6]. Biofuels tend to emerge as a major mitigation option when limited availability of carbon storage potential is assumed alongside stringent carbon constraints [7] and lack of alternative liquid fuel pathways [3,8]. The question remains if such scenarios are likely to emerge in reality.

US corn ethanol experienced measurable cost reductions during its early expansion, these were largely confined to industrial processing rather than feedstock supply, and since maize costs dominate total production costs, the scope for further technological learning is inherently limited [9,10]. Brazil's sugarcane-ethanol programme shows that first-generation fuels can scale nationally given long-term fiscal incentives, but even there competitiveness relies on cheap feedstock and continued subsidies, and the model has not diffused to other countries on purely commercial terms [11,12]. This experience demonstrates that biofuel diffusion depends less on technological potential than on specific policies. EU mandates, the US Renewable Fuel Standard, and Brazil's sugarcane model each show that sustained deployment requires exceptional institutional alignment, conditions that are unlikely to be reproduced at scale over long periods.

I argue there is a gap between models and reality that is structural. First, feedstock-dominates biofuel costs and site-specific plants suppress learning, limiting persistent cost reductions. Second, support is politically volatile and region-bound, keeping biofuels policy-dependent while faster-learning options can escape subsidy reliance. Third, energy system models commonly represent attractive end-states under idealised carbon pricing, but rarely test whether projected deployment have plausible historical analogues. This paper contributes to the growing literature in energy social science that interrogates not only technological options, but the socio-political assumptions embedded in scenario construction.

The climate benefits of biofuels have long been questioned, particularly once indirect land-use change and full supply chain emissions are taken into account [13,14]. While these concerns are central in policy debates, the argument advanced in this paper does not rest on emissions accounting; rather, it highlights structural barriers to cost reduction and scalability that persist regardless of climate benefit assessments.

2. Structural limits to cost decline

Solar modules are 99% cheaper today than in 1976 thanks to modular manufacturing and global trade [15]. Onshore wind and lithium-ion batteries show 70% and 97% cost declines since the mid-1990s [16,17]. Biofuels have exhibited no comparable learning. Two important reasons are that feedstock absorbs up to two-thirds of total

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costs and site-specific biorefineries leave little room for incremental process learning. These are precisely the structural conditions—bulky, capital-intensive systems tied to mature upstream supply chains—that innovation theory associates with low learning rates [18,19].

First-generation fuels, ethanol and hydrotreated vegetable oil (HVO), still dominate output, while repeated attempts to commercialise cellulosic ethanol have stalled. Concepts based on lignocellulosic feedstocks or gasification have likewise struggled despite two decades of public investment [20].

Nevertheless, IAM models often assign a substantial role to these technologies and assume widely differing capital costs. For example, estimates for advanced biofuel production range from below 500 to more than 2000 USD2005/kW across models [5]. Many advanced biofuel pathways, including lignocellulosic ethanol and biomass gasification with Fischer–Tropsch synthesis, have not achieved commercial deployment. Consequently, cost assumptions are derived from techno-economic assessments and engineering studies rather than mature industrial experience, contributing to the large variation in projected costs across models [2].

More importantly, capital costs represent only part of the challenge. Feedstock costs often constitute the largest share of total fuel production costs, limiting the scope for technological learning to reduce overall costs. Furthermore, as demand for sustainable biomass increases and resource constraints become more binding, feedstock costs are more likely to increase than decline over time [21].

By contrast, electrofuels also depend on feedstocks, namely hydrogen and a carbon source. However, unlike biomass, these feedstocks are produced using technologies with significant learning potential. Hydrogen can be supplied by modular electrolysers, for which learning rates above 20% have been reported for some technologies [22]. Carbon can in turn be sourced from technologies such as direct air capture (DAC), which are modular and factory-manufacturable [23]. Early DAC deployments indicate capital cost learning rates between approximately 5% and 11% and operational expenditure (OPEX) learning between 14% and 21% [24]. While the long-term cost trajectory of electrofuels remains uncertain, both feedstock and conversion costs have greater potential to decline through learning-by-doing and scale than is the case for biofuels, where costs remain fundamentally tied to biomass resources.

3. Policy dependence and instability

Energy-economic models often assume globally coherent, gradually rising carbon prices. In reality, policy support is fragmented and cyclical [25–27]. First-generation biofuels benefited from agricultural lobbying, still subsidies have been volatile. Second-generation fuels lack a strong constituency and may be even more vulnerable to reversal.

Technologies with high learning rates, such as wind and solar, benefited from targeted support in a few pioneering countries, where modular design and global tradability allowed rapid cost declines to spill over internationally. It is estimated that Germany alone contributed roughly 30% of the cost decline of solar PV up until 2012 [15]. Once competitive, solar PV and other technologies may continue to diffuse despite subsidy cuts.

Biofuels, constrained by low learning and high feed-stock costs, remain permanently dependent either on subsidies or on high carbon prices. Carbon pricing has proven equally unstable as directed subsidies, with repeals (British Columbia and Australia), and backlash (France's gilets jaunes) undermining long-term credibility. Furthermore, the world does not seem to head toward a carbon neutral future. Under current national pledges, emissions are on track for 2.8 °C of warming [28,29], and only two G20 economies are aligned with net-zero targets [30].

The role assigned to biofuels in integrated assessment models depends both on assumptions about technological progress and cost reductions in advanced biofuel production, and on the availability of strong and durable climate policies, particularly high carbon prices. The relative importance of these factors varies across models and scenarios. However, the fundamental reason biofuels occupy a prominent position in many net-zero pathways is more straightforward: most models assume that some sectors will continue to require carbon-based fuels even in a carbon-neutral future. In such settings, sustainable biofuels and electrofuels emerge as the primary alternatives to fossil fuels. The only other option is continued fossil fuel use combined with sufficient negative emissions to offset the resulting carbon releases [3].

In contrast to biofuels, electrofuels could drive rapid 'learning-by-doing' in a few pioneering jurisdictions, progressively eroding the only advantage biofuels still enjoy: relative technological maturity. Still, it is possible that no liquid fuel pathway will achieve cost parity with fossil fuels without draconic carbon prices. Whether this leads policymakers to impose such carbon prices or instead to moderate their climate ambitions remains an open question.

In the absence of substantial cost reductions, long-term competitiveness of biofuels do depend on persistent subsidies and/or sustained high carbon prices. Consequently, large-scale biofuel deployment depends either on biofuels overcoming structural barriers to cost reduction or on a future characterised by durable policy support and limited progress in competing technologies. Neither pathway is plausible. Revealed investment patterns are consistent with this assessment: despite greater technological maturity and decades of policy support, investment in advanced biofuels remains modest, while global investment in electrolysers is already roughly three times larger [31].

Besides the fiscal burden of subsidies that fail to deliver sustained commercialisation, there is a more profound policy risk in continuing down this path. If long-term competitiveness is structurally implausible, then subsidies do not merely represent wasted expenditure; they risk locking capital into assets with little prospect of operating without support. Such over-investment in technologies that cannot stand on their own creates stranded assets and distorts investment signals. More critically, the political and financial resources absorbed by maintaining biofuel mandates and subsidies may crowd out or delay the deployment of alternatives with stronger prospects for cost reduction and scalability. In this way, continued reliance on subsidies does not only impose direct public costs but may also slow the broader energy transition by entrenching fragile pathways at the expense of more robust ones.

4. Models without pathways

Many energy system models continue to assign roles to biofuels, particularly when carbon storage is constrained, despite limited empirical evidence that such deployment is achievable at scale. This reflects a deeper methodological challenge: scenarios are often constructed around a predefined climate target and then identify technology portfolios capable of achieving it [32,33]. More recently, a growing literature has questioned not only the assumptions embedded in integrated assessment models, but also how model outputs are interpreted and used in policy processes. Critics have highlighted the gap between technically feasible model pathways and pathways that remain plausible under real-world conditions of political contestation, institutional constraints, social acceptance, and deep uncertainty [34–37]. Thus, the limitations identified here are not unique to biofuels, they reflect a broader challenge in the interpretation of IAMs and energy system models.

The real-world investments is thus likely to diverge from the investments made in the modelling world. Closing that gap demands scenario work that embeds socio-technical realism [35]. However, empirical data is too scarce to robustly model the mechanism between policy support, technological development, and shifting political priorities. As a result, many of the mechanisms that ultimately determine whether a pathway can be realised are only weakly represented, or entirely absent, in model-based analyses.

This parallels Flyvbjerg's concept of the "inside view" and the "outside view" in infrastructure project [38]. The inside view evaluates a pathway based on its internal logic: if specific assumptions regarding technology costs, policies, and resource availability are satisfied, can a desired outcome be achieved? IAMs and energy system models are inherently structured around this perspective, as they rely on simplified representations and assume that key mechanisms can be adequately captured through parameterisation. However, when the underlying socio-technical and political dynamics cannot be robustly modelled, the inside view becomes insufficient for assessing plausibility [37].

The outside view instead asks whether comparable developments have occurred previously and whether there is empirical evidence supporting the assumptions required for success. Flyvbjerg demonstrated that forecasts based primarily on the inside view systematically underestimate risks and overestimate performance, whereas assessments informed by historical experience tend to provide more realistic expectations. Importantly, he also notes that reliance on the inside view is often reinforced in contexts where there are incentives to justify particular outcomes. This mirrors the work by Jewell and Cherp [37], they caution against treating stakeholder support as evidence of feasibility in climate mitigation scenarios. Actors involved in scenario development are often invested in particular outcomes and may therefore focus on identifying pathways that achieve desired goals rather than critically evaluating the likelihood that the required conditions will emerge.

Historical precedents is essential for the outside view, because they provide information about what societies have previously been able to achieve. However, for many emerging energy technologies, direct historical analogues are either limited or entirely absent. In such cases, the outside view can be extended from outcomes to mechanisms. Rather than asking whether an identical transition has occurred before, the relevant question becomes whether the mechanisms required to produce it have empirical support.

For a given scenario, this involves identifying the critical conditions necessary for success and evaluating each against historical evidence and policy experience. For example, technological learning can be assessed by examining a broader class of technologies with similar characteristics. Likewise, assumptions about policy consistency can be evaluated by drawing on evidence from technology-specific support schemes, and environmental regulation more generally, including their durability, reversals, and interaction with political cycles. Similarly, assumptions about large-scale deployment depend on sustained investment patterns, which can be compared to historical episodes of infrastructure expansion or industrial transformation [39].

The first step in such an assessment is central mechanisms and preconditions for a scenario to emerge. The second step is to examine whether these mechanisms have empirical precedents. Have similar rates of technological learning, policy persistence etc. been observed previously? Where sufficient data exists this also may even allow estimates of how frequently such developments occur. In most cases, however, the objective is not precise quantification but a more qualitative assessment of whether the required conditions are well supported, weakly supported, or unprecedented.

Yet evaluating individual mechanisms in isolation is not sufficient. A pathway may appear plausible when each assumption is considered separately, while remaining unlikely when viewed as a whole. Many scenarios depend on several conditions being realised simultaneously and sustained over long periods of time. If multiple required developments each have limited historical support, the overall plausibility of the pathway is substantially reduced. Technologies that depend on several individually uncertain developments occurring simultaneously should therefore be regarded as less feasible than technologies that remain viable across a broader range of futures. The purpose of such an assessment is not to classify scenarios as feasible or infeasible, but rather to compare their relative plausibility. Scenarios that rely on fewer and better-supported assumptions should be assigned greater credibility than those requiring multiple favourable developments with little historical precedent.

Such an approach does not replace modelling. IAMs remain essential for identifying technically feasible futures and exploring interactions across sectors. Rather, it complements modelling by introducing a systematic plausibility assessment grounded in empirical evidence. Without such scrutiny, scenarios risk presenting futures that are internally consistent yet externally implausible, providing a misleading basis for policy and investment decisions.

5. Conclusions

From an energy social science perspective, the long-term competitiveness of biofuels depends on an increasingly improbable alignment: sustained high carbon prices, generous and stable policy support, and the absence of faster-learning alternatives. Such conditions have no historical precedent in the energy sector. Even waste-based fuels, often presented as niche solutions for sectors like aviation, remain constrained by the same reasons. These structural weaknesses suggest that biofuels are unlikely to become a large-scale solution.

Climate strategies must begin with realism. Scenario exercises should subject pathways to empirical plausibility checks: do the assumed deployment rates, cost declines, and policy conditions resemble anything observed historically or in present trends? Mainly those pathways that pass such tests should inform policy. Without this discipline, elegant models risk providing false certainty and steering investments into unattainable futures.

The case of biofuels illustrates a broader challenge for climate and energy policy: the persistent gap between modelled desirability and socio-technical feasibility. Despite decades of policy support, biofuels remain structurally constrained by feedstock-dominated costs, low learning potential, and permanent dependence on politically fragile instruments. Yet they continue to feature prominently in long-term scenarios, not because of demonstrated momentum, but because models optimise toward end-states that abstract from institutional volatility, investment risk, and historical precedent.

This misalignment matters. When scenarios normalise large-scale deployment of technologies whose competitiveness depends on narrow and unlikely futures, they risk legitimising policy strategies that lock capital into fragile pathways and divert attention from alternatives with stronger learning dynamics. More broadly, it underscores the need to complement modelling with empirical plausibility checks grounded in innovation theory, political economy, and observed investment behaviour. Absent such realism, scenarios risk not only misguiding policy, but actively shaping expectations around pathways that the energy system is unlikely to deliver.

CRediT authorship contribution statement

Fredrik Hedenus: Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT in order to check English and find references. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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