Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

OPINION

View Article Online
View Journal | View Issue

Cite this: *Energy Environ. Sci.*, 2022, **15**, 3114

Received 16th April 2022, Accepted 7th July 2022

DOI: 10.1039/d2ee01244h

rsc.li/ees

Bridging capital discipline and energy scenarios

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Integrated assessment and other macro-scale energy systems models are valuable tools for exploring alternate ways (scenarios) to decarbonize an economy. A shortcoming, however, is that most models assume new mitigation assets are conceived, permitted, financed, built and commissioned overnight. In reality, it takes multiple years to develop assets, a significant fraction of which may be abandoned or shelved because various risks and/or commercial conditions do not support the investment case. New approaches that reflect developers' disciplined approach to capital allocation can improve scenario feasibility and inform the right policies and investments to assure deep decarbonization on-the-ground.

Deep decarbonization of society requires the rapid expansion and parallel withdrawal of productive capacity (electricity, fuels, materials, biomass, and so on) over time and across diverse and complex value chains. Integrated assessment and other macro-scale energy systems models are indispensable tools for exploring alternate combinations of mitigation technologies (scenarios) that could achieve this goal over a pre-determined time frame, such as by 2050.

Recently, there has been a growing emphasis on improving scenario feasibility, with calls for greater consideration of human factors[1] and finance.[2] We may be the first to make a comparable plea for the consideration of private developer decision-making. In models, developers respond rationally and instantly to market signals, building new mitigation projects overnight. In reality, developers initiate a multi-year, structured decision-process to sufficiently de-risk long-lived capital investments prior to asset financing and construction. This is an area that is scarcely dealt with in the academic literature, because of a fault-line that finds most modelers of sustainable futures on one side and risk-taking project developers on the other. Yet, it presents significant implications as to the right policies to assure deep decarbonization goals.

In this Opinion, we unpack the mechanics of asset mobilization. We start by describing an important commercial concept, known as capital discipline. We show how this concept underlies two key energy transition challenges: path-dependence and the chicken-or-egg problem. Managing these challenges is essential to achieve ambitious mitigation targets. However, it is beyond the scope of, and unreasonable to expect, macro-scale systems models to incorporate features that are so granular and heterogeneous.[3] We therefore introduce an approach to bridge the analytical gap, termed 'reverse-engineering', which is a process of interpreting energy scenarios through a developer-lens. This allows for the identification of policy and investment actions to manage path-dependence and chicken-or-egg problems, along with other execution bottlenecks. A new community of applied researchers working closely with practitioners focused on reverse-engineering could reveal critical insights needed to improve scenario feasibility.

Asset mobilization processes and capital discipline

Asset developers play a central role in the decarbonization of energy and industrial systems. The assets may be resources in the ground, or infrastructure, or specific projects. Asset development is characterized by investment hesitancy, which is overcome, if at all, by staged, disciplined decision-making that weighs risks of many kinds, from technological, to political and regulatory, to bottlenecks in materials and labor. The roots of investment hesitancy lie in uncertainty around future technology costs and performance, integration opportunities, timing of interdependent capacity, durability of policies, competition, offtake volumes and prices, supply chain constraints, litigation threats, and public acceptance of the technology and projects, all of which are location dependent. These uncertainties expose asset valuations to two key risks: (a) increased capital at risk due to cost overruns and/or delays in engineering, procurement, construction, and start-up; and (b) operating profits at risk due to revenue shortfalls or operating cost overruns. Both are exacerbated by the long-lived nature of decarbonization assets.

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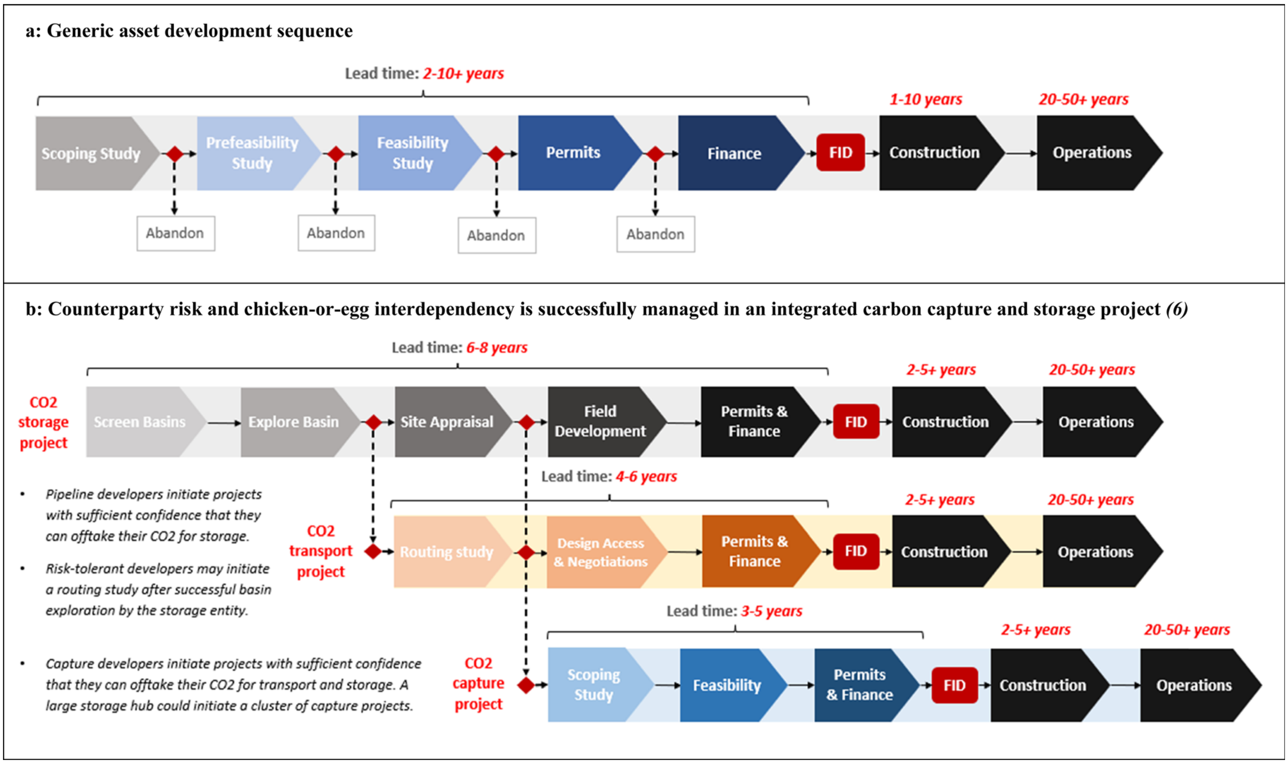


Fig. 1 Schematic representation of typical asset development sequences.

Successful asset mobilization therefore relies on a sequence of de-risking activities and decisions, which consume considerable resources and require significant lead times. First, a sequence of pre-investment development stages takes place, progressively increasing the capital at risk, to fund project conception, initial scoping, pre-feasibility studies, feasibility studies, social and environmental reviews, permitting, and financing (Fig. 1a). Each of these stages involves multiple stakeholders and tasks and has the potential to reveal information justifying project abandonment. A significant fraction of proposals typically will be shelved or abandoned before the final investment decision ("FID"). The objective of this staged approach is to minimize capital at risk prior to the FID gate, while ensuring that any project sanctioned at the FID gate generates anticipated returns on that capital. This capital (allocation) discipline is designed to maximize returns to shareholders. It is the norm for all commercial enterprises, and it is especially deeply embedded in the decisions of asset-heavy companies. Of course, such capital discipline is compromised from time to time, especially when decision-making is impacted by incentives that are not aligned with creating company value.[4]

The link between capital discipline and scenario feasibility

Modelers are well aware of two aspects of the asset developer's reality: path-dependence and the chicken-or-egg problem. These energy transition challenges become even more marked once the decision sequence behind capital allocation is explicitly considered.

Path-dependence refers to situations where policies and investments implemented today shape, and potentially restrict, the future set of available options. For example, current global investments in clean energy are flowing almost exclusively to solar, wind, and energy efficiency measures.[5] Given the lead times associated with asset development and capital formation, this may limit the potential to quickly and reliably turn to other low-carbon options, such as various clean fuels, carbon capture and storage (CCS), or nuclear power, if and when they are needed.

The chicken-or-egg problem refers to the sometimes-slow uptake of technologies because of uncertainty surrounding access to enabling infrastructure, end-use markets, and/or performance of counterparties. Chicken-or-egg problems affect new technologies, such as zero-emission vehicles and clean hydrogen, but also existing technologies, such as utility-scale renewables that are delayed or unprofitable because of transmission access risks.

Here we examine CCS, to illustrate one of many examples of the chicken-or-egg problem. The owner of a centralized industrial facility contemplating CO_2 capture might allocate capital to initial scoping and prefeasibility studies, and even secure favorable government incentives, but it will never sanction the project through FID without sufficient confidence in reliable access to CO_2 transport and storage capacity at an acceptable cost (Fig. 1b). Often, that confidence will need to be underpinned by a third-party agreement to take full responsibility for the CO_2 during the capture project's economic life and beyond. At the same time, third-party CO_2 storage operators are unlikely to invest in establishing this commercial capacity without sufficient confidence in secure supplies of CO_2 priced to satisfy the targeted return on storage investment, creating an investment stalemate.[6]

This granular consideration of path-dependence and chicken-or-egg problems is beyond the scope of integrated assessment and other macro-scale models that describe energy transitions. As a result, existing assessments can fall short of providing feasible roadmaps or identifying climate change policies needed to put countries on realistic decarbonization pathways.

Reverse-engineering as a bridge between the asset developer's and modeler's worlds

Reverse-engineering refers to the process of working backwards from a modelled level of deployment through the typical critical path planning process used by an asset developer. Reverse-engineering can be performed productively at the national scale and many subnational scales, given the highly heterogeneous conditions (technological, industrial, geographical, commercial, legal, social, *etc.*) facing developers in different settings.

Reverse-engineering proceeds in three basic steps. First, it backcasts a mitigation option from its modeled future capacity to its current state, describing the physical asset deployment requirements at a socially-relevant spatial and temporal resolution. This downscaling could use the results from integrated assessment or other macro-scale models as a starting point. Second, it overlays the asset development sequence, describing the schedule of risk-reduction activities and decisions as well as construction times related to project delivery. Third, it determines key policy and investment interventions that could accelerate the asset development sequence and increase the likelihood that the pace of deployment implied by the model can be reached.

We demonstrate reverse-engineering by describing how an asset developer would assess the scenario of delivering one billion tonnes per year of CCS in the US in 2050 as in Princeton's Net-Zero America (NZA) study (Fig. 2, showing scenario E +).[7] While NZA is a classic integrated assessment, in this particular case reverse-engineering was performed by one of us (CG) for CCS, which was then incorporated into the final results.[8] In the first decade, significant upfront investments in CO_2 storage and transport are directed toward the chicken-or-egg problem. At a cost of roughly \$100 billion, most of the nation's CO_2 storage resources are characterized and almost the entire national trunk pipeline system is built. This investment lays a foundation for the wide adoption of CO_2 capture projects, ninety per cent of which come after 2030. This non-linearity suggests that 'build it and they will come' investments are likely to be necessary to assure feasible paths to net-zero by ambitious future dates, like 2050.

In contrast, policy instruments for CCS today primarily support CO_2 capture, with little parallel activity in storage or infrastructure (pipelines). Even at a large-scale, this approach is unlikely to stimulate the speed and scale of CCS adoption needed to meet ambitious goals, as it fails to address the chicken-or-egg problem. Similarly, government co-investments and/or the political prioritization of iconic, flagship demonstrations can also compromise capital discipline, by rewarding the completion of projects despite their questionable long-term viability.

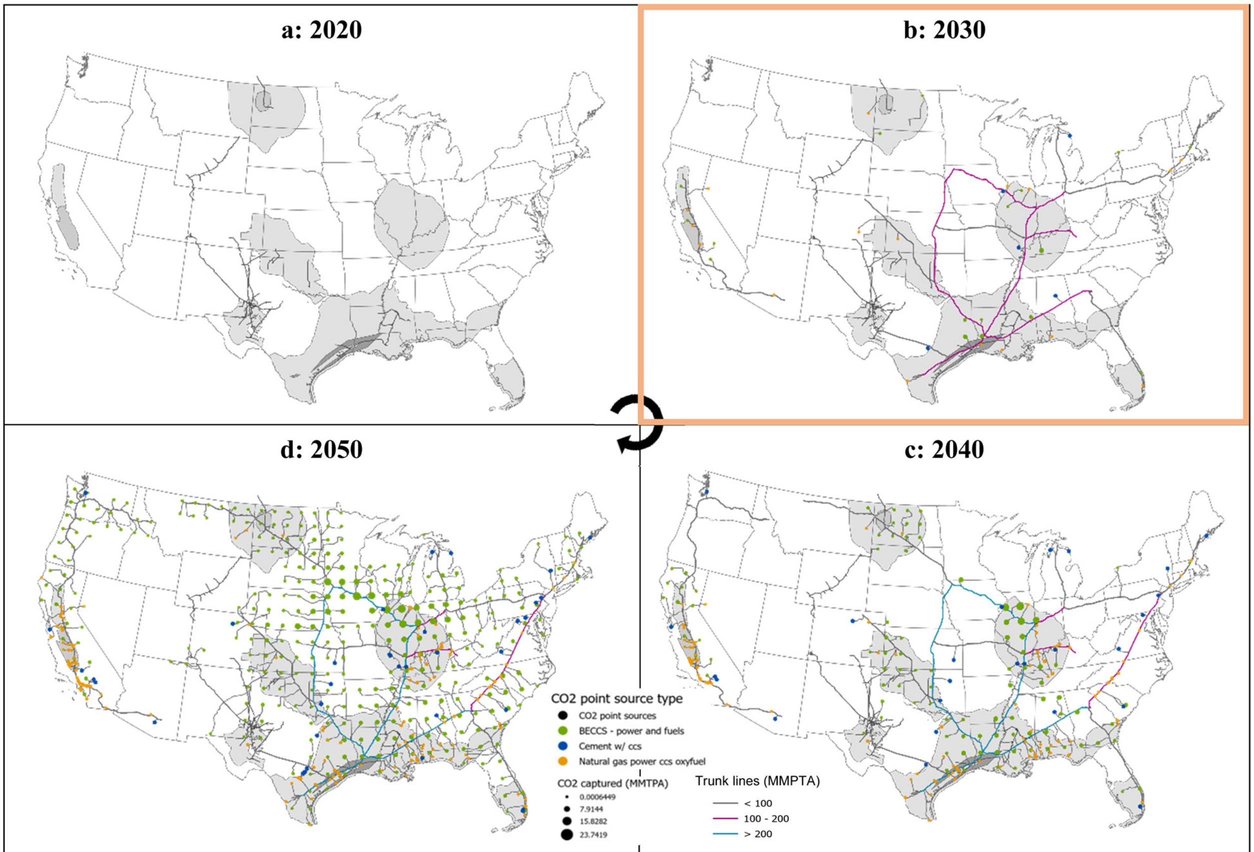
Storage and transport investments are arguably the most important set of interventions to de-risk CCS investment decision-making, but there are other no-regrets, 'system-oriented' interventions that would increase the odds of rapid and broad-scale adoption, including: streamlining regulatory processes leading to permits; performing CO_2 spur pipeline routing studies; sorting out long-term liability; performing or supporting the preparation of environmental impact assessments; facilitating consensus-building and land-owner access negotiations in local communities; and providing incentives based on tons of CO_2 that are captured and stored.

We note that incumbent developers may downplay certain system-oriented interventions. For example, an incumbent's access to regional resource data and ability to navigate complex regulations could create competitive advantages over new market entrants. It is in the incumbent's interest to crowd-out competition. In contrast, the rationale for system-oriented interventions is to achieve economy-wide deep decarbonization on a relatively rapid time schedule, by crowding-in competition. This implies a needed role for governments to execute strategic investments and policies.

Reverse-engineering can also inform practicable optionality

Reverse-engineering exposes some poorly understood challenges associated with technology optionality in climate change mitigation. Researchers and policymakers often acknowledge uncertainty in future projections, but point to optionality as a tool to remedy faltering progress with a planned pathway. In practice, such optionality implies the capability to 'pivot', with minimal delay, to the rapid expansion of alternative technology options. Reverse-engineering shows that significant investments may be needed to keep alternatives practicably pivot-ready. Meanwhile, it is possible that these options may never be exercised, resulting in significant redundant investments. In the case of our CCS example however, this seems unlikely given the heavy reliance on CCS in the vast majority of deep decarbonization scenarios.[9,10]

Reverse-engineering may reveal other structural challenges related to practicable optionality. For example, a plan to pivot to CCS in the event that a renewables-heavy pathway falters must not disregard the potential for significant contraction in oil and gas production and consumption during the time before the pivot. Diminished asset values and revenues for oil and gas companies may well reduce their appetite to invest in CCS. To preserve a pivot to CCS, planners could adopt clear, transparent, and durable policies and regulations that drive oil and gas producers to coordinate the phase down of their



e: Investments

Year	Investments in CO_2 storage characterization ($ mil.)[1]	Investments in CO_2 pipeline infrastructure ($mil.)[1]	Investments in CO_2 injection wells facilities ($mil.)[1]	CO_2 transported and stored (Mtpa)[2]
2020	-	-	-	80
2025	1,500	3,900	-	80
2030	8,600	78,800	2,300	145
2035	13,000	141,700	10,700	326
2040	13,000	149,800	18,500	516
2045	13,000	167,700	40,000	767
2050	13,000	230,500	47,900	1,009

[1] *Cumulative new capital investments*
[2] *Includes 80 Mtpa existing CO_2 transport and injection for enhanced oil recovery, the majority of which is extracted from natural subsurface deposits of CO_2*

Frames a-d show one example of the decadal build-out of a system which captures and (geologically) stores 1 $GtCO_2/yr$ in 2050. Frame e tabulates the estimated investments and CO_2 volumes by half-decade.(8)

The orange highlight reveals the possible non-linear nature of chicken-or-egg investments: one third of the total CCS investment is made by 2030, for only an additional 65 Mt (or 6-7%) of the required 1 Gt of mitigation.

Cost-minimizing energy-systems models do not emphasize optionality investments that would reduce the risk of mitigation target shortfall, as such methods do not assume the possibility of unplanned energy transition bottlenecks.

Fig. 2 Required investments to solve the chicken-or-egg problem to deliver a 1 billion tonnes/year CCS system in the US in 2050.

unmitigated production with their switch to CCS and renewables portfolios.

A new community of researchers and practitioners to advance reverse-engineering

The overnight deployment of energy and industrial assets in macro-scale models stands in stark contrast to the often-lengthy sequence of decisions and investments to reduce uncertainty, mitigate risk, and deliver long-lived decarbonization projects and infrastructure. Bridging this gap is essential to assure net-zero plans that are feasible and robust. Success in doing so will require new forums that bring together applied researchers, asset developers and engineering firms working collaboratively on reverse-engineering for different sectors, technologies, regional settings, and speeds and scales of aggregation. Such collaborations would probe the model-developer fault-line related to processes of asset mobilization more deeply, and establish core principles, methodologies, and terminology for a reverse-engineering discipline.[11] Early steps should include a range of focused workshops whose results are shared widely with many audiences, specifically including policymakers and practitioners involved in energy transition asset development.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

We thank Dr Martin Parkinson from Macquarie University and Prof Paul Dargusch from The University of Queensland for their comments on an early draft of this manuscript.

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