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Maintaining capital discipline in the rush to net-zero energy systems

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Abstract

Achieving ambitious net-zero targets will involve executing large, often interdependent, capital projects across multiple value chains at unprecedented speed. We use a mixed methods approach to explore potential risks associated with speeding up deployment. Like in other sectors, we find that energy transition projects have a history of underperformance in terms of cost and time. Such underperformance can arise due to a variety of unforeseen challenges affecting supply chains, community opposition, regulations, and scope changes, among others. Engaging with experienced clean energy practitioners suggests that recent efforts to accelerate the transition and aggressive time-limited incentives may result in less accurate estimates of expected performance, and lead to more frequent delays, cost overruns, and even project failures for clean energy infrastructure. To limit underperformance, there is a need to strengthen capabilities within public institutions to assure value through robust selection and oversight of projects, manage expectations so specific successes do not create unrealistic expectations and specific failures do not erode public support, and capture and disseminate lessons learned and adapt plans in response to learnings.

Main Text

Introduction

The need to rapidly reduce global CO_2 emissions was globally recognized with the Paris Agreement in 2015. Individual nations have defined their independent, nationally determined commitments for decarbonization. Still, these commitments will not prevent global average temperatures from rising above the critical 2^{o}C, and a significant increase in the speed of decarbonization is required (1). Encouragingly, an increasing number of nations, states, cities, and firms have announced mid-century net-zero commitments, suggesting a major acceleration in decarbonization activities could be imminent (2).

Deep decarbonization of the economy will involve profound changes in production, distribution, and use of energy vectors. The mix of vectors will change, with electricity projected to play an increasingly dominant role as sectors are increasingly electrified, including those traditionally dependent on fossil fuel combustion, such as passenger road transport and heating. Less mature technologies like carbon capture, utilization and storage (CCUS) and emerging energy carriers like electrolytic (E) hydrogen will also expand to decarbonize sectors that are not readily electrified. This paper focuses on large-scale infrastructure for clean energy supply and industrial decarbonization that large private and public organizations deliver.

Models that inform net-zero pathways suggest that the level of investment in clean energy and industrial decarbonization infrastructure must increase by 2.5 to over six times business-as-usual capital investment rates for the sector (3,4,5). This suggests a dramatic acceleration in the execution of large, often interdependent, capital projects, for example, wind and solar capacity increasing more than 10-fold together with a 3-fold expansion of transmission. Such models also project thousands of clean hydrogen and fuels production facilities along with thousands of carbon capture and storage (CCS) projects, both supported with associated pipeline and storage network infrastructure. To achieve and sustain such rapid investment and deployment, these projects must be implemented in a manner which avoids unintended adverse social, environmental, and financial consequences. However there has been scant research or commentary regarding the potential for such unintended consequences to in fact increase as the pace of deployment increases.

In this Perspective, we explore potential risks arising with such a dramatic acceleration of infrastructure investment in the energy and industrial sectors as they transition to low-carbon technologies. We adopt a mixed method approach in which we report: (a) A quantitative analysis of reported cost and schedule performance data from historical capital projects relevant to the net-zero transition; and (b) Qualitatively explore the potential for an erosion of project development discipline (and performance) in response to recent policy-driven efforts to speed up deployment, through interviews undertaken with a diverse group of very senior energy sector professionals. Our hope is that this article might encourage reflection among academics, policymakers, and industry professionals as to the need to assess and manage potential risks associated with very rapid energy transition. With trillions of dollars of investment at stake, failure to do so could have serious implications for the durability of policy, public support, energy costs, and energy transition progress.

The Essence of Capital Discipline in the Energy Transition

Energy systems models typically simulate investors, developers, and stakeholders (writ large) with durable, collective support for the transition, near-perfect foresight or confidence in long-term enabling policy, and perfect visibility across sectors and supply chains. Furthermore, these actors cooperate seamlessly and execute flawlessly to develop and build projects *instantaneously* as needed to balance energy supply and demand while reducing emissions at minimum cost (6). In reality, companies, consumers, and communities engaged across the energy and industrial ecosystems may be sceptical about policy durability, may not share common objectives, and are often motivated by various individual values, self-interest, and profit maximization. Furthermore, developers of capital projects typically follow a deliberate *capital discipline* process involving multi-year or even multi-decadal lead times for development, permitting, financing, and construction (7).

Capital discipline is practiced to ensure that projects deliver their intended value and is characterized by an investment decision sequence through which each project is progressively de-risked through various activities and studies. A project arrives at a final investment decision (FID) only after the developer has gained an acceptable level of confidence in the project valuation. This means the project developer and associated investors are satisfied that all technical, industrial, market, financial, social, environmental, and political risks and uncertainties have been adequately mitigated or that suitable contingency plans are in place to assure the project valuation. In an ideal world, having passed the FID milestone, every project would be implemented flawlessly, delivered safely, on time, for the approved capital budget, and achieve all performance criteria defined in the feasibility study throughout the project life (6).

Research on infrastructure project performance shows that the above ideals are seldom the case. Capital discipline is often compromised due to a combination of optimism bias and misaligned incentives (8, 9). As a result, estimates of project schedules, costs, and commercial benefits that investors rely on at FID retain significant uncertainty. This means that few projects are actually delivered for the estimated cost, within the estimated time, and/or deliver estimated commercial and other benefits (10). Research has also repeatedly shown that such uncertainties are adversely skewed. Energy projects are no exception with scholars highlighting the persistent tendency for cost overruns across a broad array of energy technology projects (11, 12). Energy *megaprojects* have been especially prone, especially large-scale hydroelectric power projects in Brazil (13), and nuclear projects (14, 15). Gumber et. al. (16) examined more than ten thousand renewable generation projects, reporting persistent, and indeed worsening, delays in timelines for all types and sizes of renewable projects this century. This suggests that major infrastructure, industrial projects, and energy projects alike, are more likely to experience overruns than underruns in both time and cost. The magnitude of overruns is also likely greater than the magnitude of any underruns, and projects are more likely to underachieve, than to meet or exceed anticipated benefits.

Simply put, the norm of large capital projects, being over budget, over time, and under benefits (a pattern that has been coined "The *Iron Law* of megaprojects" (17)) is a problem for the clean energy sector. This work considers whether these characteristics are likely to remain prevalent throughout the energy transition, especially with growing efforts to accelerate the transition, and addresses what prudent policies, development procedures, approval processes, and oversight protocols might be put in place now to safeguard against overpromising and underdelivering.

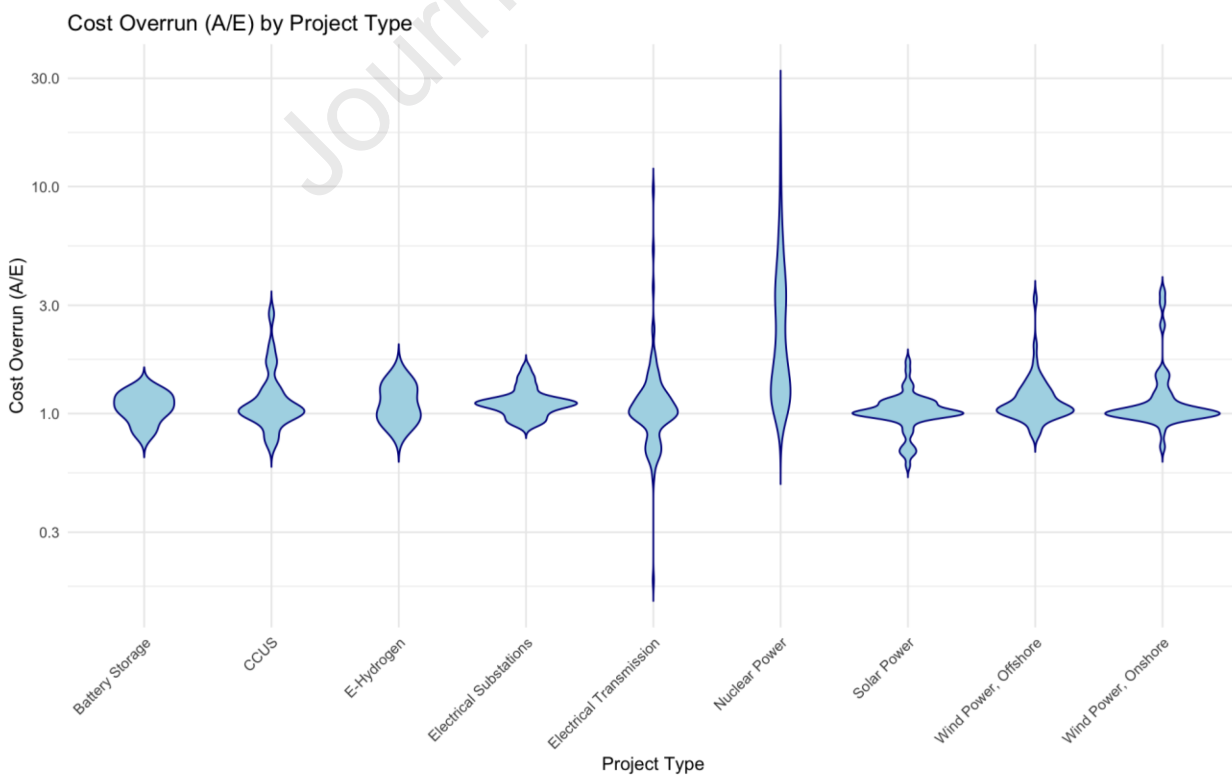
In the net section we examine how clean energy projects have historically performed against their approved cost and time estimates, using available data dating back to 1980, and whether that performance has shifted since 2000, when climate drivers began to influence energy sector investments.

Evidence of the *Iron Law* in past energy transition projects

We assembled a dataset of over 1,100 clean energy and industrial decarbonization (net-zero) projects undertaken worldwide (for raw data, see SI-1), with data on cost overruns available for 482 projects and schedule overruns for 401 projects. Access to data is somewhat limited since project developers are not compelled to disclose differences between final delivered project costs, and the prior estimates at project conception or FID upon which capital allocation decisions were based. Our data were sourced from a wide range of materials, including investment papers, business cases, progress reports, project closeout reports, press releases, public proposals, peer-reviewed journals, government publications, financial statements, and contractor reports. In addition to these secondary sources, we gathered data directly from owner organizations. For instance, we launched a data-sharing initiative to collect transmission line data to obtain information on completed electricity transmission and substation projects worldwide. This initiative operated on a *quid pro quo* basis, where participants gained access to the full anonymized dataset in exchange for their project data contributions, engaging utilities, transmission system operators (TSOs), and generation companies globally.

The dataset includes the approved project budget and schedule at FID and the actual outturn cost and schedule at the commercial operation date (COD) for projects completed between 1980 and 2023. Note that there is a 'survival bias' in this dataset, as it includes only successfully financed and built projects. Projects conceived with optimistically low estimates that experienced considerable escalation from conception through feasibility studies and which failed to pass FID are not included. Many CCS aspirants in the first decade of this century fall into this category (18).

Figure 1 summarizes the cost and schedule performance of different categories of energy transition projects.



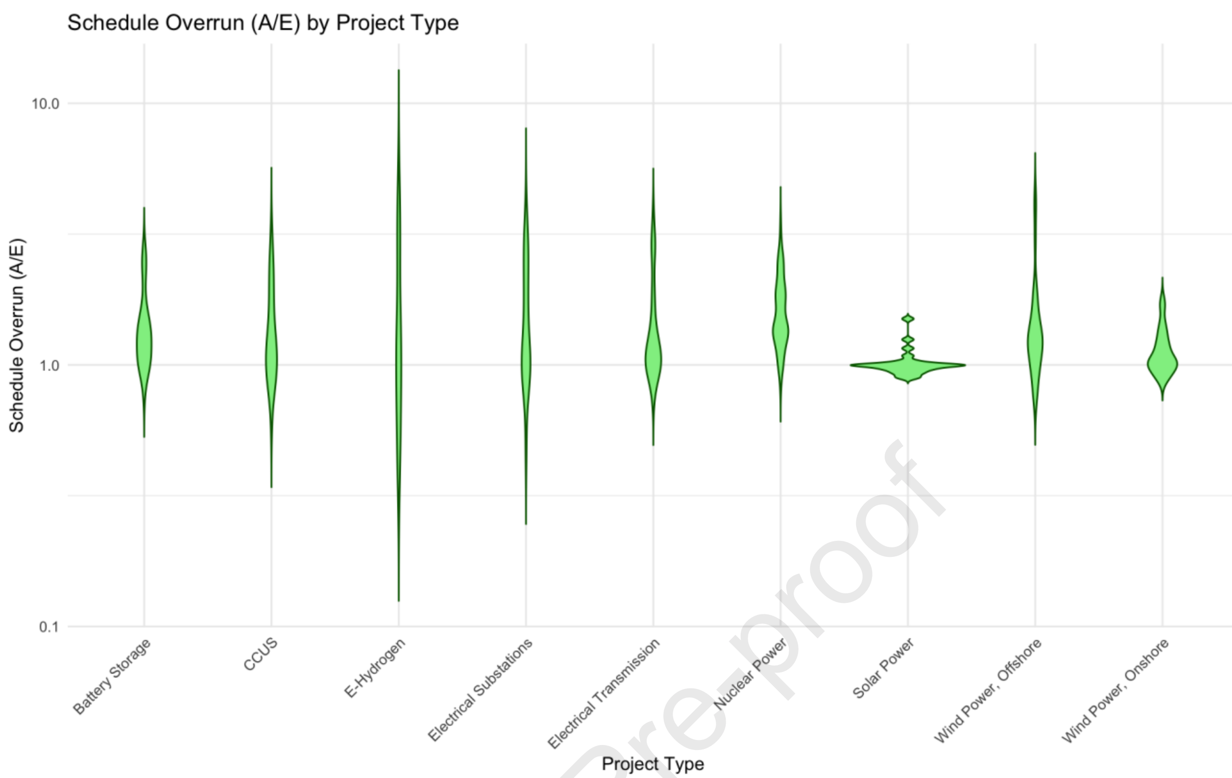


Figure 1 Historical overruns in capital cost (top panel) and schedule (bottom panel) experienced in clean energy and industrial decarbonization projects. Overruns are calculated as the real-term ratio of actual (A) divided by the estimate at FID (E) in local currency. Data are shown on a log scale. Project numbers for each project technology type are provided in Table SI1.1.

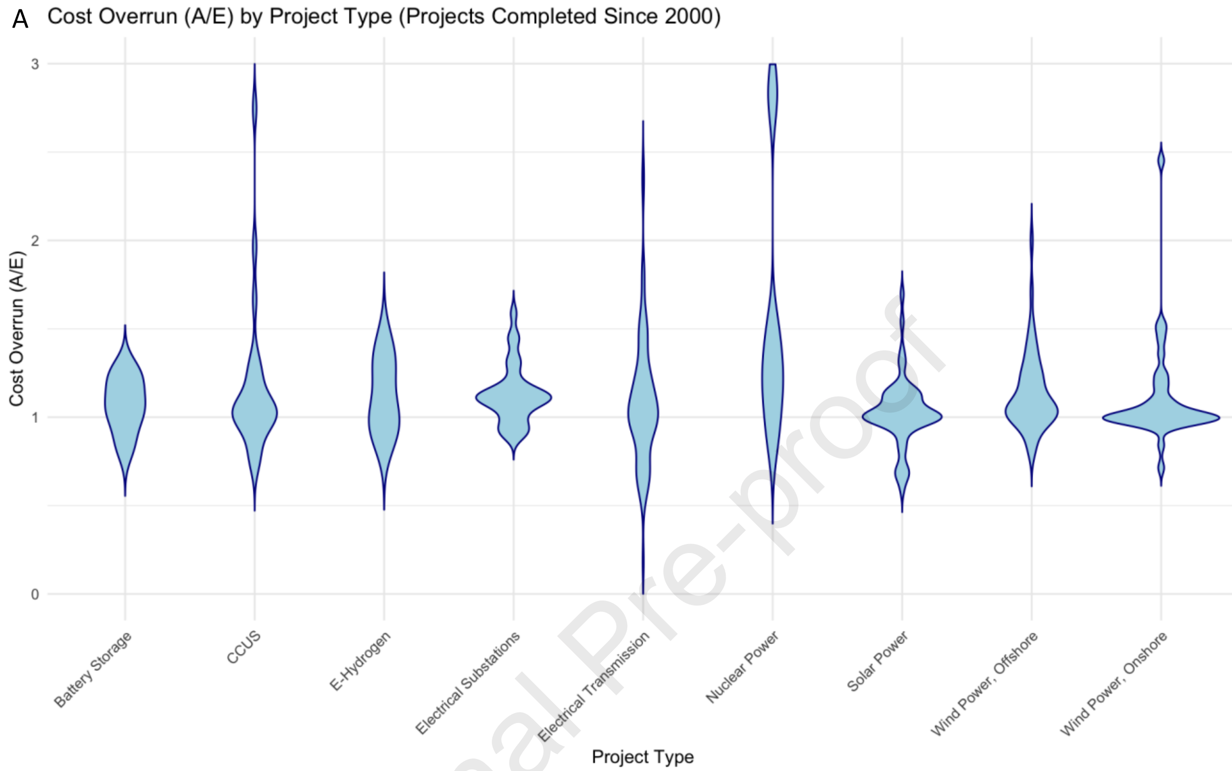
While the results in Figure 1 need to be treated with caution given the varying numbers of projects represented, they indicate a consistent and significant departure from the cost and schedule estimates approved at FID across all technologies. The worst performing technologies have been nuclear power on cost and electrolyzed hydrogen for schedule. The best-performing technology is solar generation, which has been more consistently delivered closer to budget and schedule than all other technologies.

Our statistical analysis (see SI-1.2) on net-zero projects, employing one-sample t-tests and Wilcoxon signed-rank tests to assess cost and schedule overruns, unequivocally shows that net-zero energy projects are victims of the *Iron Law*. We observed significant statistically significant overruns across the different types of projects in our sample, with mean cost overrun of 1.84 (one-sample t-test: $t = 9.81$, $p = 3.8e-21$; Wilcoxon: $V = 96008$, $p < 2.2e-16$) and schedule overrun ratios of 1.51 (one sample t-test: $t = 15.62$, $p = 1.4e-43$; Wilcoxon: $V = 62055$, $p < 2.2e-16$). This result is strongly influenced by the well-documented cost and schedule escalation that impacted nuclear deployment in the U.S. and France after the early successes of the 1960s and 70s (19).

Excluding Nuclear Power projects from the analysis yielded much reduced yet still significant overrun ratios of 1.17 for cost and 1.39 for schedule, indicating a persistent trend of overruns across project types.

Figure 2 presents the data limited to projects completed since 2000 to focus on more recent influences. This timeframe more realistically represents the influence of climate drivers on energy and industrial investment.

A



B

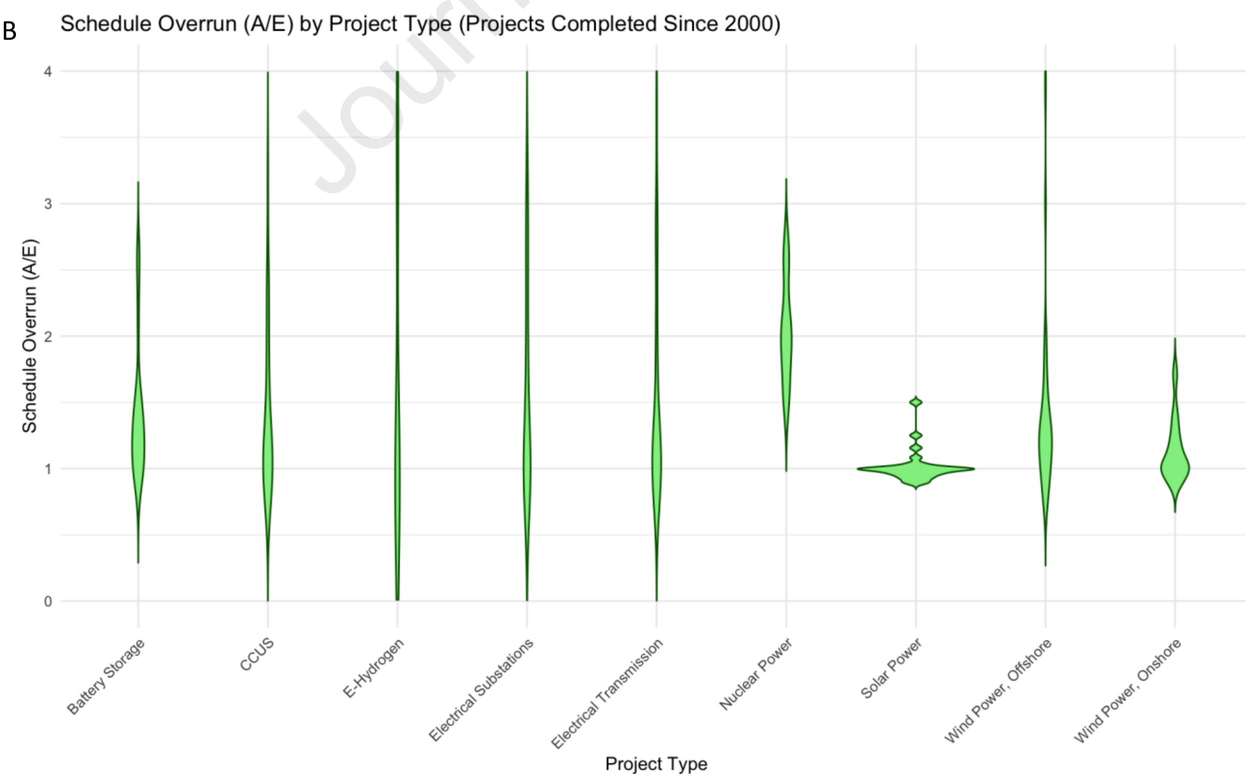


Figure 2 Historical overruns in capital cost (top panel) and schedule (bottom panel) experienced in clean energy and industrial decarbonization projects. Overruns are calculated as the real-term ratio of actual (A) divided by the estimate at FID (E) in local currency. Data are shown on a log scale. (limited to projects completed since 2000). Project numbers for each project technology type are provided in Table SI1.2.

When limiting the analysis to projects completed since 2000, we observe a mean cost overrun of 1.36 (t-test: $t = 3.74$, $p = 1.13e\text{-}4$; Wilcoxon: $V = 24125$, $p = 7.91e\text{-}13$) and schedule overrun ratios of 1.39 ($t = 8.35$, $p = 4.54e\text{-}15$; Wilcoxon: $V = 14860$, $p = 6.24e\text{-}16$). This indicates that statistically significant overruns remain prevalent even in recent years, though the magnitude is somewhat reduced compared to the entire sample.

The relatively more predictable cost and schedule outcomes for solar generation are noteworthy. Solar PV is characterized by a more modular equipment characteristic, a standardized approach to design compared to other energy transition technologies, and a manufacturing-type approach to site works. It has also benefited from a steep decline in panel costs over recent decades, which is likely to have compensated for cost overruns typical of other technologies. In essence, these features have meant that equipment costs, at the time of procurement, were reliably lower than estimates made before FID, except for a period of disrupted supply chains due to COVID-19 and trade restrictions with China. Future developments will be instructive in tracking whether solar PV continues to deliver more predictable outcomes over the coming decades and, indeed, if and how similar benefits might be replicated for other technologies.

Risks arising from incentives to accelerate deployment

Though the recent expansion of renewable electricity generation is encouraging, renewable generation still only contributes 12% of global electricity generation, and clean energy resources (mostly wind, solar, hydro, biomass, and nuclear) only account for 11% of global primary energy consumption. A recent wave of major policy initiatives backed by generous incentives aims to boost clean energy deployment significantly. In the US, policymakers passed the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA), potentially catalyzing $1 trillion or more from the public and private sectors. European policymakers also introduced a suite of policy packages, such as Fitfor55, the Green Deal Industrial Plan, REPowerEU, and the Net Zero Industry Act, to ramp up clean energy deployment, build manufacturing capacity to support the energy transition and reduce dependence on Russian energy imports. These policies often have or may be perceived to have, a limited time horizon – either via an explicit expiry date or uncertain political durability. Such perceptions of a limited window might motivate project proponents to rush and even circumvent capital discipline protocols to capture maximum value from the incentives (20).

Furthermore, headwinds from strained supply chains and workforces, community opposition to siting, and transmission infrastructure bottlenecks are already holding back the deployment of onshore wind and solar. Meanwhile, high expectations for offshore wind in the US and green hydrogen globally face even greater challenges (21). This inevitably increases the demand for more complex emerging technologies, such as carbon capture and storage including direct air capture of carbon, potentially facing even longer and more challenging development pathways (22). While these technologies may capitalize on the existing skills and workforce in the oil and gas sector, supply chains are less mature, and they potentially face even sterner opposition from communities and environmentalists (23).

It is also instructive to explore how project developers respond to more potent policies and incentives, especially given the perception that these are time-limited, and to explore how developers respond to the inclusion of more complex emerging technologies. Will capital discipline be compromised further as project proposals increasingly feature less mature project definitions, lower design maturity, and solutions with lower technology and commercial readiness? Accordingly, will more projects, based on overly optimistic estimates of costs, schedule, and benefits, underperform?

We employed a qualitative expert elicitation approach to assess the potential impact of speeding up deployment that has been driven by recent generous incentives on applying capital discipline protocols in energy transition projects. This involved conducting 45- to 60-minute semi-structured interviews with a limited set of 20 energy sector senior executives. These 20 executives were selected from the first author's (a 25-year veteran in energy and resources project development prior to joining academia) network to be somewhat broadly representative of energy asset owners, project developers, and EPC (engineering, procurement, and construction) contractors. These executives were selected based on their seniority, diversity of experience in developing and deploying a variety (in some cases all) of the clean energy, industrial decarbonization technologies considered in this Commentary, along with critical minerals projects. Each was invited by an email and agreed to participate on the condition that no statements would be attributable to any of them or their organization. The research plan including the recruitment approach and interview questions received ethics approval from the Princeton Institutional Review Board. Hereinafter, the interviewees will be referred to as the participants (experience profiles are described in SI 2.1). Participants' experience covered large-scale solar PV, onshore and offshore wind, utility-scale batteries, high voltage transmission, nuclear power, CCUS, and clean hydrogen/fuels projects, with total project values ranging from \$100 million to over \$5 billion, in the US, Europe, UK, Middle East, and Australia. All participants had at least 15 years of experience across multiple clean energy and industrial decarbonization technologies, and critical minerals processing. Several also had considerable experience in conventional fossil energy projects during their careers. All participants claimed experience in pre-FID development activities, with about half having experience in construction and commissioning, and six participants also had experience in operations during their careers.

The complete interview guide (including context and questions) is provided in SI 2.2. Participants were asked a series of questions under four main lines of inquiry:

(i) Participant's role, sector, experience, and regional focus (Figure SI 2.1).
(ii) Participant's familiarity and expectations with "capital discipline."
(iii) Participant's experiences and expectations with generous incentives to accelerate technology and infrastructure deployment.
(iv) Participant's expectations of clean energy transition policies and progress.

Participant responses are summarized in Table 1 and in the following narrative.

All participants considered themselves to be 'extremely familiar' with capital discipline protocols as defined and considered it critical to maximizing value and limiting loss in projects. All participants suggested that the usual amount of time spent on Pre-FID activities (de-risking projects) was typically about the same as the time spent during the construction and commissioning of projects, with five participants noting occasional exceptions. "*The burning platform: some utilities face growing concerns about the reliability and resilience of networks as the penetration of weather dependent renewable* *generation grows, and are pushing investments in batteries and grid firming on a fast track"* (P5); and "*Pre-FID times of major projects can also occasionally end up very much longer than the construction period due to market conditions that force the company to put a hold on major capital"* (P20). This point was echoed by three other participants. At the same time, another suggested that "*some of the very large companies can be a bit bureaucratic and get stuck in decision paralysis"* (P8).

Most participants (18 of 20) expected that truncated, less rigorous application of capital discipline would somewhat increase the number of completed projects, with the remaining two anticipating no change because, for example, "*They might try to go forward, but they will generally fail to attract project finance"* (P14). However, consistent with their unified view of the criticality of robust application of capital discipline and making productive use of the pre-FID window, all participants agreed that truncated, less-rigorous pre-FID activities would result in fewer (15 of 20 participants) or, at best, no change (5 of 20) to the number of projects actually completed within budget, on schedule, and delivering against benefits. Additionally, all participants anticipated *some* increase in the number of projects that will be completed but exceed estimated schedules and budgets.

Participants were mostly in agreement (17 of 20) that when companies with limited experience in the energy sector seek to participate in major energy transition projects, they tend to truncate and compromise the processes and practices. One participant added that *"…inexperience tends to come with a level of optimism bias and often they aren't familiar with the main safety hazards… and don't understand how the supply chains work… the result is that things can really go south fast..."* (P2). Several respondents also mentioned that the involvement of experienced individuals in new start-up companies was not guaranteed to bring the same degree of capital discipline characteristic of companies with a long track record in the same or adjacent sectors.

Most respondents were sceptical about the durability of policies, with most (13 of 20) believing that policies would at least persist until the next change of government. Most participants, especially those with experience in Europe, had confidence that policy changes would not affect completed investments already in operation. Several (5 of 20) participants, all with experience in the EU and/or MENA, indicated they expected policies to be durable for the life of investments made. Two participants from APAC were more sceptical, suggesting policies can be vulnerable to abandonment in the event of surging energy prices. Overall this scepticism in policy durability has the potential to diminish expectations for accelerated clean energy deployment.

All participants felt that recent incentives, have attracted more companies to the sector, which 12 of the 20 reporting some increase, and eight reporting a large increase. Most (15 of 20) participants also felt that generous incentives, introduced to encourage deployment, somewhat increase the number and value of projects being developed, financed, and completed. Five participants expected no change, with one commenting, *"These policies are certainly driving a big surge in project announcements, but a lot won't convert"* (P9). Another participant noted that *"a lot of private entrepreneurial equity is being thrown around, but to get through FID, you have to satisfy the banks that you have a robust project and the experience to deliver"* (P13). Notably, developers of renewable power (wind and solar) projects were unanimous in their view that recent incentives are materially increasing the level of investment and deployment of projects.

Most (15 of 20) participants expected no change in the number of projects completed on time, on budget, and performing as intended. In contrast, three participants expected some increase, and two expected a reduction, in the number of projects completed on time and budget. Most (17 or 20) participants expected some growth in the number of underperforming projects. One participant specializing in solar, wind, and battery deployment acknowledged that *"clean energy projects tend to run long on schedules and have lately gone through cost escalation between initial investment decisions and final completion…"* but added: *"I don't think the reasons for those escalations at this point are as much about green-driven enthusiasm as they are about the many varied challenges of infrastructure project execution in our industry"* (P19).

There was unanimous concern among participants about the risks associated with time-limited policies and incentives for example, where eligibility depends on construction commencing before a specific date. One issue related to the entry of inexperienced companies to the sector. One participant emphasized that "*whether or not new entrants can last, depends on existing barriers to entry"* (P7), with another noting that "*new entrants often make big announcements without following through, including some very high-profile entrepreneurs who do have a track record say in tech or mining, and have thrown serious money at projects for no result*" (P12). Others (P11, P14, and P18) referred to a growing ecosystem involving venture capital, private equity, and start-ups pouring money into technology and demonstration proposals across multiple emerging technologies including CCUS, direct air capture, advanced geothermal energy, green fuels, and advanced nuclear, "*…many of which have no real prospect of ever delivering value"* (P14).

Participants were divided on the extent to which time-limited policies and incentives resulted in truncated pre-FID activities. Seven of the 20 participants expected *somewhat more* companies to truncate pre-FID activities, and 13 participants observed *most companies truncate pre-FID activities*. One participant from a large, diversified energy company suggested that *"it's likely most, [companies truncate pre-FID activities] … particularly due to pressure to secure pre-commitment capital [for long-lead procurement items], even if it involves taking unacceptable risks and meeting impossible deadlines"* (P4). Another participant highlighted: *"In this sector [large-scale green hydrogen/ammonia], there were and still are a lot of start-ups or even wealthy entrepreneurs who started out with big plans but are now retreating rapidly. The problem is finance. These projects are mostly too large to finance on balance sheet, and they aren't robust enough to attract project finance"* (P10).

Overall, most participants, believed that current incentives like the United States IRA, the EU Green Deal, and REPowerEU would likely encourage investment but lead to unexpected consequences, resulting in positive but insufficient progress. The two exceptions suggested that these incentives generate hype and will ultimately fall short of expectations. One participant offered: *"In general, the world just has not yet grasped the scale and speed of energy transition and what it takes to develop and finance all of these major projects"* (P19). Similarly, most expressed a high level of doubt about the ability of countries to meet climate goals.

Table 1 Summary of industry executives' responses to interview questions

	extremely	generally	vaguely	not very	unsure
Familiarity with Capital Discipline	20	0	0	0	0
	negligible	small	~ half	majority	unsure
Pre-FID time vs overall time for development and construction	0	0	20	5*	0
	Critical	somewhat	minimal	not at all	unsure
Importance of consistent and rigorous application of capital discipline for good project performance	20	2**	0	0	0
	large	some increase	no change	reduce	unsure
Impact of truncated and less rigorous capital discipline on number of projects completed	0	18	2	0	0
	large increase	some increase	no change	reduce	unsure
Impact of truncated and less rigorous capital discipline on number of projects completed in line with performance targets			5	15	0
	large increase	some increase	no change	reduce	unsure
Impact of truncated and less rigorous capital discipline on number of projects that underperform	0	20	0	0	0
	increase rigor	similar	compromised		unsure
Capital discipline rigor by new entrants vs experienced counterparts	1	2	17		0
	large increase	some increase	no change	reduce	unsure
Impact of generous incentives on number and value of projects completed	0	15	5	0	0
	large increase	some increase	no change	reduce	unsure
Impact of generous incentives on number and value of projects completed in line with performance targets		3	15	2	0
	large increase	some increase	no change	reduce	unsure
Impact of generous incentives on number and value of projects completed that underperform targets	3	17	0	0	0
	permanent	investment life	Unstable	change of gov	unsure
Assumed longevity of generous incentives announced by governments	0	5	2	13	0
	large increase	some increase	no change	reduce	unsure
Impact of generous, time-limited incentives on number of companies entering the sector	8	12	0	0	0
	large increase	some increase	no change	reduce	unsure
Impact of generous, time-limited incentives on number of experienced, competent companies entering the sector	0	0	20	0	0
	most	some increase	no change	reduce	unsure
Proportion of companies truncating pre-FID activities when generous, time-limited incentives are on offer	13	7	0	0	0
	adequate, well designed & ir	investment but in	create mostly hype	the needle on	unsure
Expectations of generous government incentives (e.g. IRA, and international equivalents) on energy transition	0	18	2	0	0
					unsure
Major countries and sectors that look well placed to achieve their stated net-zero goals?	2 respondants suggested countries with extraordinary (firm) renewable resources (hydro, geothermal) e.g., Norway, Iceland, Brazil				18
					unsure
Major countries and sectors look worst placed to achieve their stated net-zero goals	1 respondant suggested suggested United States due to political partisanship				19

* Answered 'about half' but qualified with exceptions - e.g. of projects stalled during ecoomic cycles, or compressed in response to a 'burning platform'

** Answered 'critical for maximizing value and limiting loss, but qualified with exceptions - large companies sometimes paralyzed by bureacracy

Color coded by number of responses	19-20	14-18	10-13	6-9	3-5	0-2

Limitations

Our study has limitations in relation to both quantitative datasets, and qualitative interview samples. First, while there are thousands of clean energy and industrial projects completed world-wide each year, but there is limited detailed reporting of estimated costs, schedules and benefits at conception, FID, and COD. There also exists variations in terminology and reporting that could affect the data. While we took all reasonable efforts to validate data, including engaging with developers, uncertainties remain. Our expert elicitation process was likewise limited in sample size. Relying on the authors' networks, we limited the sample to experts with at least 15 years (and mostly >20 years) of experience in the actual development and delivery of clean energy and industrial capital projects, with exposure across multiple technology types, and across multiple and regions. Such senior executives bring a range of challenges, including time schedules, disclosure concerns, company restrictions. Nonetheless, our study did manage to engage an impressive list of 20 seriously experienced executives for roughly an hour each.

Notwithstanding these limitations, both the quantitative and qualitative findings are sufficiently consistent that our chief concern is valid - that aggressive policies and incentives designed to accelerate the energy transition could result in diminished capital discipline that exacerbates already widespread project underperformance in the sector. Left unremedied, such concerns have the potential to seriously compromise the speed and scale of progress toward net-zero targets.

Discussion and Conclusions

A clean energy transition is underway, thanks largely to technology innovation, global collaboration, and policy initiatives that have driven precipitous falls in the costs of solar photovoltaic, wind, and lithium ion batteries (24,25). Despite this recent progress, the energy transition remains in its infancy, and to achieve climate targets, almost all countries must dramatically increase deployment rates of clean energy and industrial decarbonization infrastructure to meet their net-zero goals. Our assessment of the historical deployment of most prospective clean energy and industrial decarbonization technologies supports findings from past studies that these projects, like major civil infrastructure and complex processing plants, generally tend to overrun cost and time estimates. Engaging with senior executives and experts involved in the energy transition also offers evidence for a potential worsening of this trend as an unintended consequence of well-intended policy intended to speed up the transition.

As policymakers worldwide try to catalyze investment in renewable electricity generation and other clean technologies, we find that the allure of generous incentives is attracting new entrants to participate in the transition. According to experienced industry professionals who we interviewed as part of this study, many of these new entrants seem unfamiliar with risks and uncertainties in these sectors, which results in the ill-disciplined allocation of capital. Furthermore, incentives are often time-bound to avoid locking in excessive subsidies, which might burden consumers and taxpayers. For example, policies are often accessible only if construction (or operations) commence before a specific date and then expire within the asset's economic life. Industry professionals that we interviewed, suggested that such conditions are encouraging truncation and compromise in capital discipline protocols designed to maximize value and minimize investment losses among new entrants and even experienced incumbents.

These trends are cause for concern. They could signal a potential increase in the frequency and magnitude of project cost overruns, delays, and benefit shortfalls, or worse, project failures, with hundreds of billions of dollars at risk.

Mature technologies like wind and solar generation, which are generally considered bankable, at least in OECD countries are potentially shielded from the worst effects, as they rely on project finance, through commercial banks providing low-cost credit at FID, to complete construction of major projects. (26,27) With their low risk tolerance, commercial lenders insist on rigorous due diligence that generally rejects underprepared projects prior to FID. While this helps limit the capital at risk to pre-FID investment, which our data suggests is 5-10 percent of the total investment cost (for wind and solar), it can crowd out higher value opportunities.

For emerging technologies like clean hydrogen and fuels production, carbon removal, and advanced nuclear, projects are currently considered too risky and unable to access project finance due to a combination of higher capital costs, technological uncertainties, and policy risks (28). This is especially so when they involve novel energy carriers or novel applications in end-use markets, without access to established supporting infrastructure networks that were available to early deployment of wind and solar (29 below). The development and construction of such projects is conditional on the availability of sufficient and durable market incentives and must rely almost exclusively on higher-cost developer equity and venture capital for capital. Governments have an even more crucial de-risking role to play, that goes beyond correcting market failures, but rather involves market-shaping and -making roles, investing in shared infrastructure, backstopping demand, and taking lead equity and debt positions (29,32,31). Indeed, special-purpose state investment banks played just such a crucial role in financing early deployment of renewable technologies in the UK, Germany, and Australia, among others (32).

In contrast to early-mover deployment of wind and solar technologies, the first- and early-mover commercial-scale projects for these emerging technologies often involve multi-billion-dollar capital investment levels - several times that of a typical large-scale wind or solar project, and perhaps an order of magnitude larger than the early projects that catalyzed their commercialization. This means fewer projects, with larger amounts of capital of capital at risk, and likely slower cost declines as a result of learning by doing. Furthermore, if our concerns about eroding capital discipline in the policy-driven rush to net-zero prove well-founded, then we may see these larger investment proposals being subject to inadequate rigor and due diligence.

Increased frequency of cancelled or failed projects will reduce investors' risk appetite and potentially diminish political support for such technologies. This, in turn, reduces the availability of development capital and increases the cost of capital, slowing down delivery and increasing the overall cost of the net-zero transition. Maintaining rigorous capital discipline suggests that policymakers and project developers ought to *go slow to go fast*. But such a mantra will seem to many, to be in conflict with the urgency of the climate crisis. The challenge will therefore be to find the *right pace*.

We conclude that policymakers should expect higher failure rates. Key stakeholders need to adjust their risk appetite. Better collaborative and risk-sharing models must be developed with increased transparency to maximize acceptance and learning across the project delivery ecosystem. Ultimately, there is a need to strengthen capabilities within public institutions to assure value through robust selection and oversight of projects, manage expectations so specific successes do not create unrealistic expectations and specific failures do not erode public support, and capture and disseminate lessons learned, and continuously evolve, policies, incentives, and delivery plans in response to learnings.

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Supplementary Information

SI 1.1 Project Data and Analysis

This section provides an overview of the raw data used to analyze cost and schedule overruns in clean energy and industrial decarbonization projects. Data were collected for over 1,100 projects globally, covering a range of asset types, including battery storage, CCUS, e-hydrogen, electrical substations, electrical transmission lines, nuclear power, solar power, offshore and onshore wind power, spanning from 1980 to 2023. However, cost overruns could only be calculated for 482 projects, and schedule overruns for 401 projects, based on complete data availability.

Data were compiled from various sources, directly from organizations and from investment papers, business cases, progress reports, project closeout reports, press releases, and public proposals.

Distribution by Geographic Region

Table X shows the distribution of projects by continent, along with the proportion of projects with cost and schedule overrun data within the respective datasets. In the entire dataset, most projects with available data are in North America and Europe, followed by Asia and Oceania. In the subset of projects completed since 2000, Europe and Asia have more projects with available data, while North America's share is comparatively smaller.

Table SI1.1: Geographic Distribution of Projects by Continent (Full Dataset and Projects Completed Since 2000)

Region	Projects with Cost Overrun Data (Full)	Projects with Schedule Overrun Data (Full)	Percentage of Cost Overrun Data (Full)	Percentage of Schedule Overrun Data (Full)	Projects with Cost Overrun Data (2000+)	Projects with Schedule Overrun Data (2000+)	Percentage of Cost Overrun Data (2000+)	Percentage of Schedule Overrun Data (2000+)
North America	167	113	34.6%	28.2%	59	34	22.8%	16.0%
Europe	145	136	30.1%	33.9%	84	74	32.4%	34.9%
Asia	113	105	23.4%	26.2%	62	58	23.9%	27.4%
Oceania	45	41	9.34%	10.2%	45	41	17.4%	19.3%
Africa	8	4	1.66%	1.0%	6	3	2.32%	1.42%
South America	4	2	0.83%	0.5%	3	2	1.16%	0.94%

The percentages represent the proportion of projects with available cost or schedule overrun data out of the total projects with such data in the dataset.

Distribution by Project Type

Table Y provides a breakdown of projects by type, showing the number and proportion of projects with data available for cost and schedule overruns within the respective datasets. In the dataset, nuclear power and electrical transmission projects dominate, followed by wind and solar power. However, in the subset of projects completed since 2000, electrical transmission and wind power projects (both offshore and onshore) have a more significant representation, while nuclear power has a relatively smaller proportion.

514 **Table SI1.2: Distribution of Projects by Type (Full Dataset and Projects Completed Since 2000)**

Project Type	Projects with Cost Overrun Data (Full)	Projects with Schedule Overrun Data (Full)	Percentage of Cost Overrun Data (Full)	Percentage of Schedule Overrun Data (Full)	Projects with Cost Overrun Data (2000+)	Projects with Schedule Overrun Data (2000+)	Percentage of Cost Overrun Data (2000+)	Percentage of Schedule Overrun Data (2000+)
Nuclear Power	192	181	39.8%	45.1%	10	4	3.86%	1.89%
Electrical Transmission	119	33	24.7%	8.23%	81	22	31.3%	10.4%
Wind Power, Offshore	38	34	7.88%	8.48%	37	33	14.3%	15.6%
Solar Power	34	25	7.05%	6.23%	34	25	13.1%	11.8%
Electrical Substations	32	43	6.64%	10.7%	31	43	12.0%	20.3%
Wind Power, Onshore	27	24	5.6%	5.99%	27	24	10.4%	11.3%
CCUS	23	30	4.77%	7.48%	22	30	8.49%	14.2%
Battery Storage	10	24	2.07%	5.99%	10	24	3.86%	11.3%
E-Hydrogen	7	7	1.45%	1.75%	7	7	2.7%	3.3%

515 The percentages represent the proportion of projects with available cost or schedule overrun data
516 within each dataset (cost or schedule).

517

SI 2.1 Characteristics of Industry Professionals Interviewed (Participants) – in chronological order of engagement

Participant	Experience					
	Years	Geography	Role	Company Sector	Project Types	Project Phase
P1	10-20	APAC	SVP	Asset Owner, Developer	Diversified	Pre-FID
P2	20-30	North America	VP	Asset Owner, Developer	Diversified	Pre-FID, Construction
P3	>30	USA	MD	Asset Owner, Developer	RE	Pre-FID
P4	>30	UK, EU, MENA	SVP	Asset Owner, Developer	Diversified	All
P5	20-30	APAC	VP	EPC(M)	RE, Tx, Storage	All excl Operations
P6	20-30	APAC	MD	Asset Owner, Developer	Diversified	All
P7	20-30	EU	VP	EPC(M)	RE, Tx, Storage, Clean Fuels	Pre-FID
P8	20-30	APAC, North America	VP	EPC(M)	RE, Storage, Clean Fuels, CCS	Pre-FID
P9	20-30	North America	VP	Asset Owner, Developer	Clean Fuels, CCS	All
P10	20-30	APAC	VP	Asset Owner, Developer	RE, Clean Fuels	Pre-FID
P11	20-30	North America, UE, APAC	VP	EPC(M)	Nuclear	Pre-FID, Construction
P12	20-30	APAC	VP	Asset Owner, Developer	Clean Fuels, CCS	All
P13	20-30	North America	PM	Asset Owner, Developer	Clean Fuels, CCS	Pre-FID
P14	20-30	North America	VP	EPC(M)	RE, Clean Fuels	Pre-FID
P15	20-30	APAC, MENA	SVP	Asset Owner, Developer	Energy Transition Minerals	All
P16	20-30	MENA	VP	EPC(M)	Diversified	All
P17	20-30	EU	Dept Head	EPC(M)	RE (Wind)	All
P18	20-30	North America, EU	CEO	Government Agency	RE, Nuclear	All
P19	20-30	North America	MD	Asset Owner, Developer	RE	All
P20	20-30	North America	SVP	EPC(M)	RE, Tx, Storage, Clean Fuels, CCS	Pre-FID, Construction

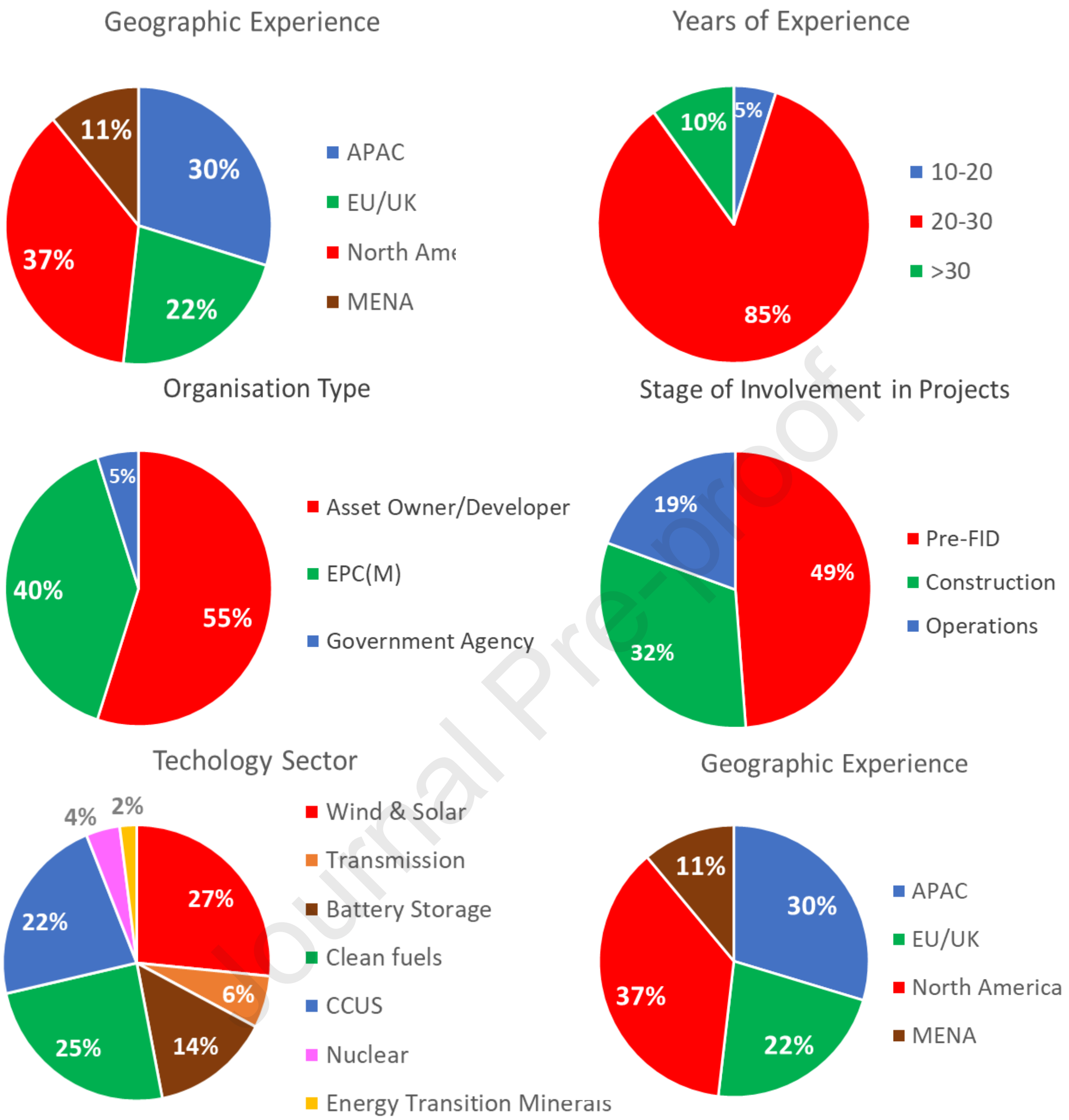


Figure SI 2.1 Graphical representation of the experience of Interviewees.

SI 2.2 Guide for Interviews with Industry Professionals

The implications for capital discipline protocols in accelerated net-zero transitions.

Interview Questions

Interview Guide:

- Questions about your role, sector, experience, and regional focus.
- Questions about your experiences and expectations with "capital discipline." [1]
- Questions about your experiences and expectations with generous incentives to accelerate technology and infrastructure deployment.
- General questions regarding clean energy transition policies and progress.

For all questions:

Please feel free to answer from the examples or to otherwise comment and to elaborate or qualify.

---

[1] We use the term capital discipline to describe the typical project investment decision sequence followed by project owners and investors. To manage the amount of capital at risk, project developers proceed in deliberate fashion, increasing their investment exposure in stages. As shown in the stylized (and simplified) representation of the typical sequence below, the stages are *decision-gated*, meaning decisions to advance from one stage to the next are subjected to rigorous reassessment of project risks and value proposition. (7)

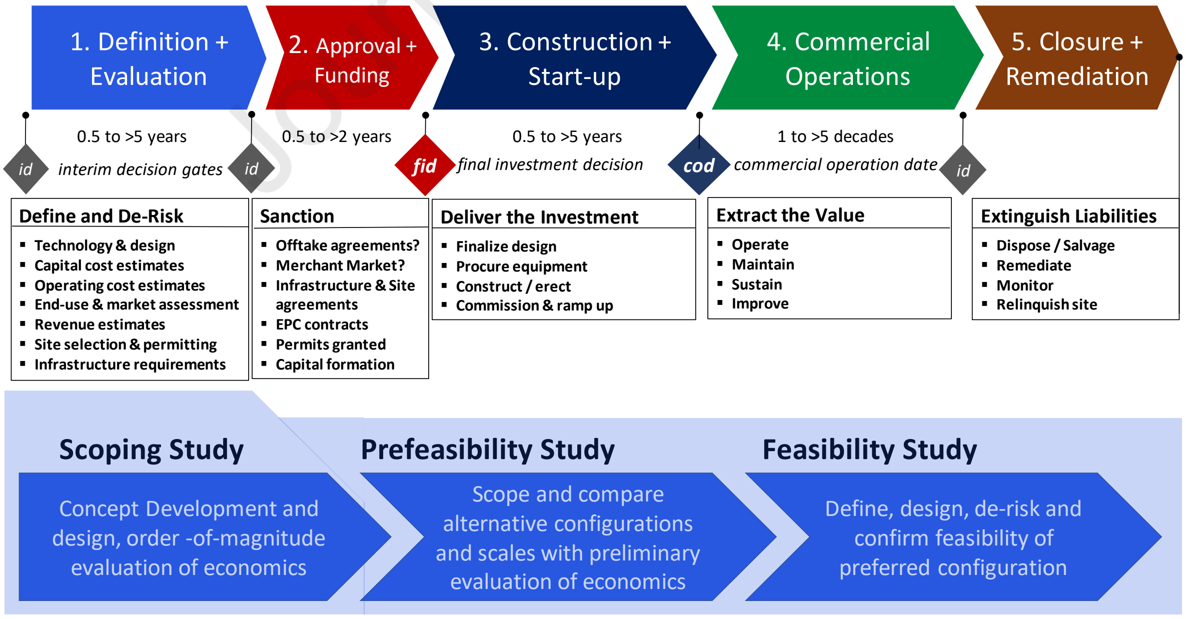


Figure adapted from Greig et al. (7)

Questions about your role, sector, and experience

1. **What type of organization do you most closely represent?** e.g.: Asset owner; project developer; investor; service provider or consultant; equipment providers; contractor or builder; government agency
2. **What best describes your role?** e.g.: Board member**;** CEO; direct report to CEO; Head of Department SVP/VP; project manager
3. **With which of the following technologies do you have most experience?** e.g., Renewable electricity generation; hydropower; energy storage; transmission; clean fuels and hydrogen production; carbon capture and storage; nuclear power; traditional fossil fuel extraction and utilization; or mining and processing of energy transition metals.
4. **What typical size of project (TIC) best describes your experience?** e.g., \$10 – \$100 M; \$100 – \$500 M; \$500M - 1B; 1 – \$5 B; >\$5 B.
5. **At what stage of projects have you mostly been involved?** e.g., Development up to final investment decision (FID); construction; commissioning; operations; several or all of these stages?
6. **How many years have you been working in your sector?** e.g.: >5 years; 5 - 10 y; 10 - 20 y; >20 y.
7. **In what regions/countries do you have most experience?** e.g., North America; Central & South America; Europe; Asia Pacific; Middle East and North Africa; other (please specify).

Questions about your attitude to "capital discipline"

1. **Is this kind of process (as described in the figure on page 1) one with which you are**: e.g., extremely familiar; generally familiar; vaguely familiar; or not familiar?
2. **For projects of the sector, type and location with which you are most experienced, is the time for Pre-FID activities relative to the overall time for development and construction;** e.g., negligible; a small fraction; around half; or the majority. Some clients with a burning platform who have very short lead times e.g. \$1B battery project 6 months pre-FID vs 1.5 year construction – the exception but working with companies increasing time pressures. (e.g. network stability). A bit unique to regional more vulnerable networks
3. **In your opinion, is the consistent and rigorous application of such capital discipline processes**: e.g., Critical for maximizing value and limiting loss; somewhat helpful in optimizing use of capital; adds time for minimal value add; a complete waste of time with no benefit? But study processes to get to FID with rapidly emerging tech with changing costs and performance, e.g., solar/batteries/wind, technology changes through the project cycle. Studies have to be repeated – never-ending process of scope renewal. Need a rethink or we'll never build anything. Especially with PPA
4. **In your opinion, if pre-FID activities were significantly truncated and less rigorous, would you expect the number of projects that are financed and built and which perform and are on time and on budget to**: e.g., e.g., increase a lot; increase somewhat; stay about the same; or reduce?

5. **In your opinion, if pre-FID activities were significantly truncated and less rigorous, would you expect the number of projects that are financed and built and which underperform (time, cost, and/or performance) to**? increase a lot; increase somewhat; stay about the same; or reduce?

6. **In your opinion, how do companies approach capital discipline when they work in a sector significantly outside their experience**: e.g., take much more time and apply much more rigor; follow similar processes and practices as experienced counterparts; or truncate and compromise the processes and practices. Some of the companies with burning platforms haven't built projects for a decade or more have lost the knowledge. Majority of companies we work with insist on discipline.

Questions about your expectations based on your experience, when generous policies and incentives to accelerate development are offered.

1. **In your experience do generous incentives and/or procurement standards to encourage deployment lead to the number and value of projects being developed, financed and completed**: e.g., increasing dramatically; increasing somewhat; staying about the same; or reducing?

2. **In your experience do generous incentives and/or procurement standards to encourage deployment lead to the number and value of projects being completed on time, within budget and to performance specifications**: e.g., increasing dramatically, increasing somewhat; staying about the same; or reducing?

3. **In your experience when generous incentives and/or procurement standards are announced by governments, what do you assume about their likely longevity**: permanent and strengthening over time; stable over the life of any major investments that get built; highly uncertain, with potential to be abandoned if energy prices increase; stable until the next change of government?

4. **In your experience, when generous incentives are offered for a limited time (e.g. available for projects that reach FID/COD before 2030/2035) does the number of companies entering the sector**: e.g., increase dramatically; increase somewhat; stay about the same; or reduce?

5. **In your experience, when generous incentives are offered for a limited time (e.g. available for projects that reach FID/COD before 2030/2035) does the number of experienced competent companies participating in the sector**: e.g., increase dramatically; increase somewhat; stay about the same; or reduce?

6. **In your experience, when generous incentives are offered for a limited time (e.g. available for projects that reach FID before 2030) what portion of companies participating in the sector tend to truncate pre-FID activities**: e.g., most; significantly more; about the same; or fewer?

Closing Questions

1. **Do you think strong policies and incentives to support the energy transition, like those available in the United States IRA, the EU Green Deal and REPowerEU, and other variations around the world are**: e.g., generally adequate, well designed and being well implemented such that they will likely spur the required clean energy deployment to achieve emissions reduction

goals; will spur investment but have the potential for unexpected consequences that might lead to positive but inadequate progress; will create more hype but fall well short of anticipated goals; fail to move the needle on mid-century net-zero targets?

2. **In your view which, if any, major countries and sectors look well placed to achieve their stated net-zero goals?**

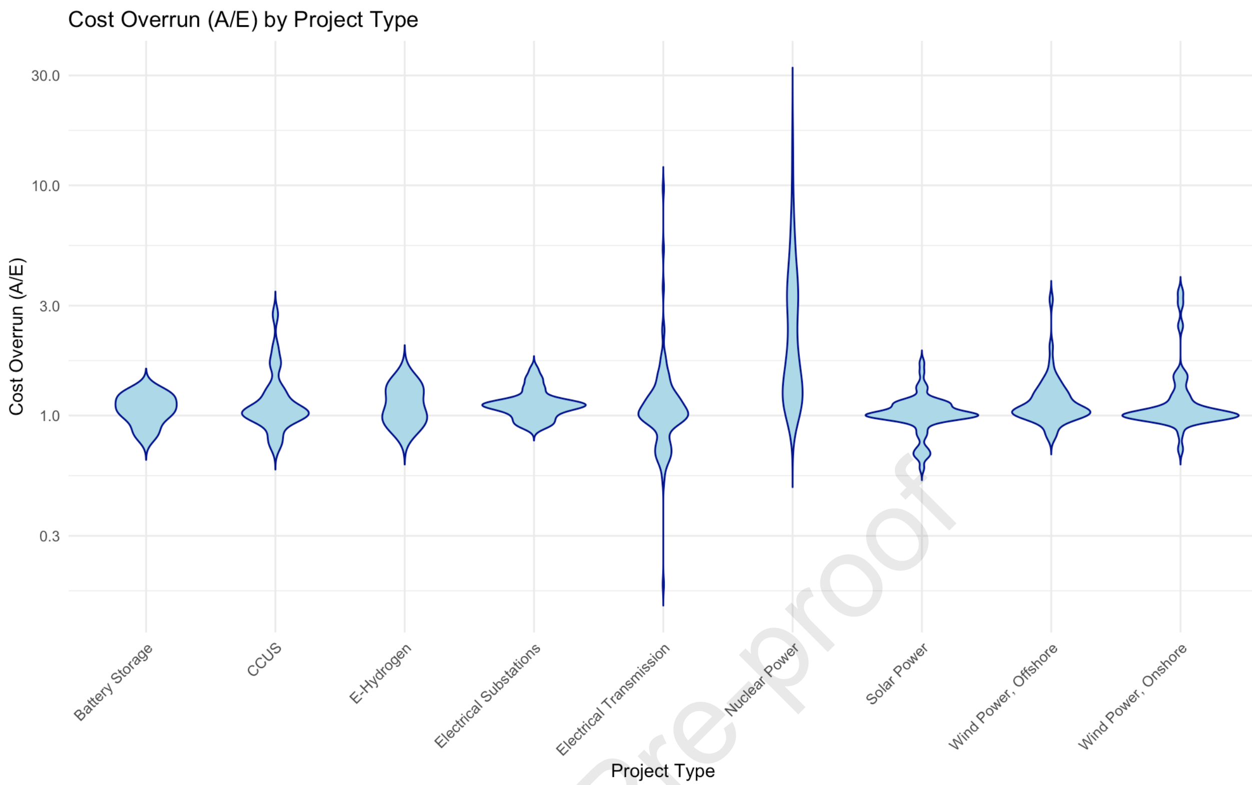
3. **In your view which, if any, major countries and sectors look worst placed to achieve their stated net-zero goals**?

	extremely	generally	vaguely	not very	unsure
Familiarity with Capital Discipline	20	0	0	0	0
	negligible	small	~ half	majority	unsure
Pre-FID time vs overall time for development and construction	0	0	20	5*	0
	Critical	somewhat	minimal	not at all	unsure
Importance of consistent and rigorous application of capital discipline for good project performance	20	2**	0	0	0
	large	some increase	no change	reduce	unsure
Impact of truncated and less rigorous capital discipline on number of projects completed	0	18	2	0	0
	large increase	some increase	no change	reduce	unsure
Impact of truncated and less rigorous capital discipline on number of projects completed in line with performance targets			5	15	0
	large increase	some increase	no change	reduce	unsure
Impact of truncated and less rigorous capital discipline on number of projects that underperform	0	20	0	0	0
	increase rigor	similar	compromised		unsure
Capital discipline rigor by new entrants vs experienced counterparts	1	2	17		0
	large increase	some increase	no change	reduce	unsure
Impact of generous incentives on number and value of projects completed	0	15	5	0	0
	large increase	some increase	no change	reduce	unsure
Impact of generous incentives on number and value of projects completed in line with performance targets		3	15	2	0
	large increase	some increase	no change	reduce	unsure
Impact of generous incentives on number and value of projects completed that underperform targets	3	17	0	0	0
	permanent	investment life	Unstable	change of gov	unsure
Assumed longevity of generous incentives announced by governments	0	5	2	13	0
	large increase	some increase	no change	reduce	unsure
Impact of generous, time-limited incentives on number of companies entering the sector	8	12	0	0	0
	large increase	some increase	no change	reduce	unsure
Impact of generous, time-limited incentives on number of experienced, competent companies entering the sector	0	0	20	0	0
	most	some increase	no change	reduce	unsure
Proportion of companies truncating pre-FID activities when generous, time-limited incentives are on offer	13	7	0	0	0
	adequate, well designed & im	investment but in	create mostly hype	the needle on	unsure
Expectations of generous government incentives (e.g. IRA, and international equivalents) on energy transition	0	18	2	0	0
					unsure
Major countries and sectors that look well placed to achieve their stated net-zero goals?	**2 respondants suggested countries with extraordinary (firm) renewable resources (hydro, geothermal) e.g., Norway, Iceland, Brazil**				18
					unsure
Major countries and sectors look worst placed to achieve their stated net-zero goals	**1 respondant suggested suggested United States due to political partisanship**				19

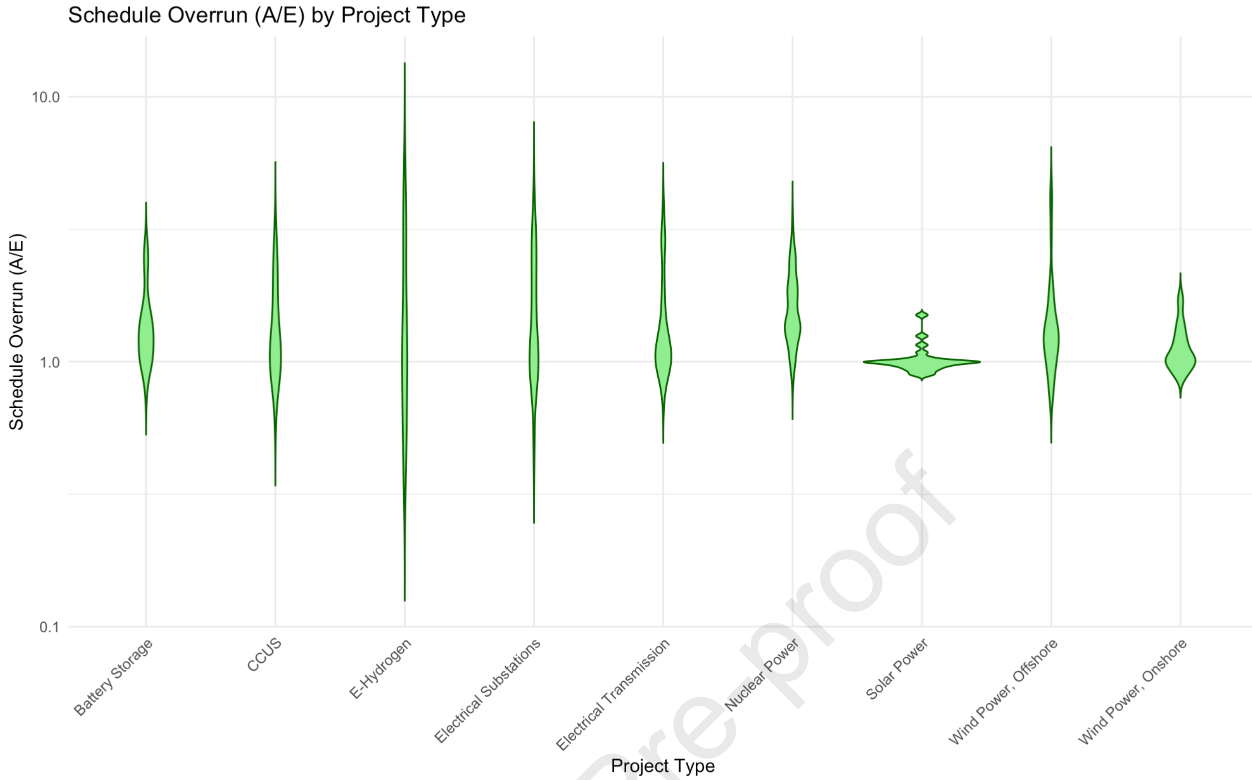
* **Answered 'about half' but qualified with exceptions - e.g. of projects stalled during ecomomic cycles, or compressed in response to a 'burning platform'**

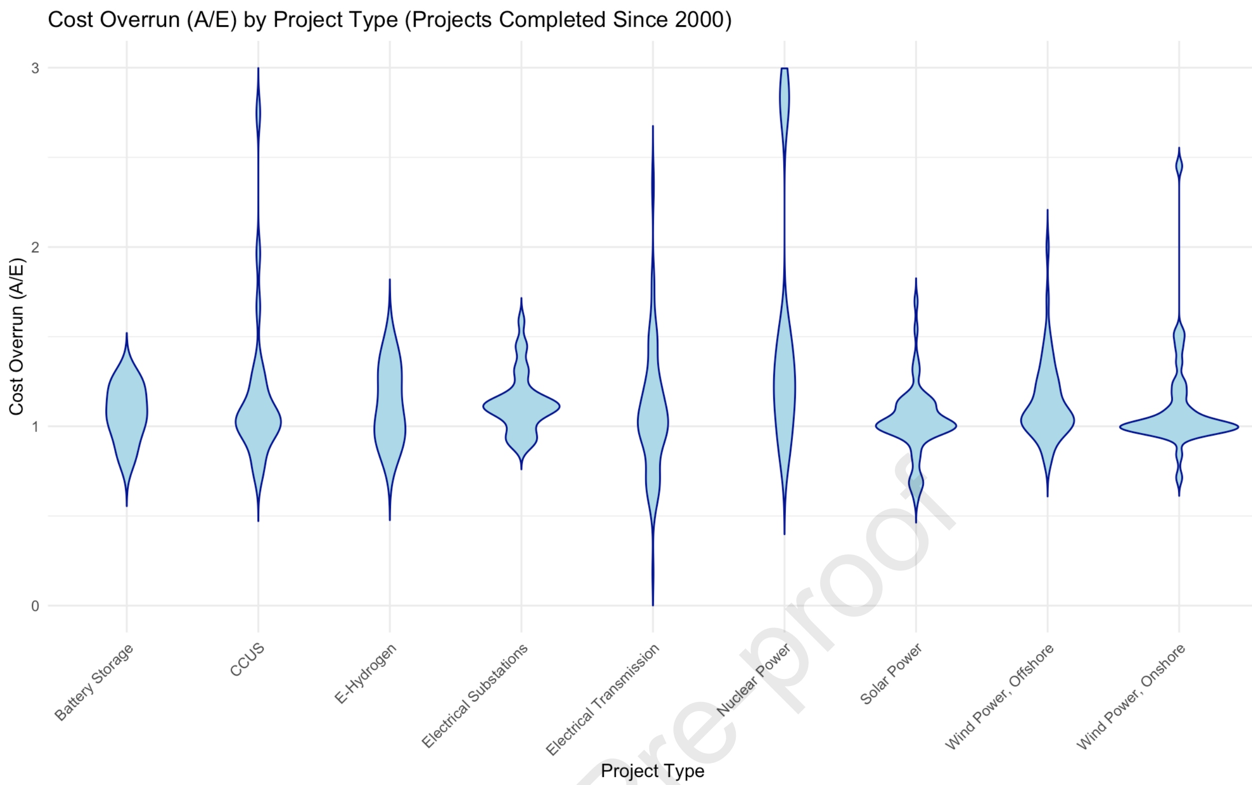
** **Answered 'critical for maximizing value and limiting loss, but qualified with exceptions - large companies sometimes paralyzed by bureacracy**

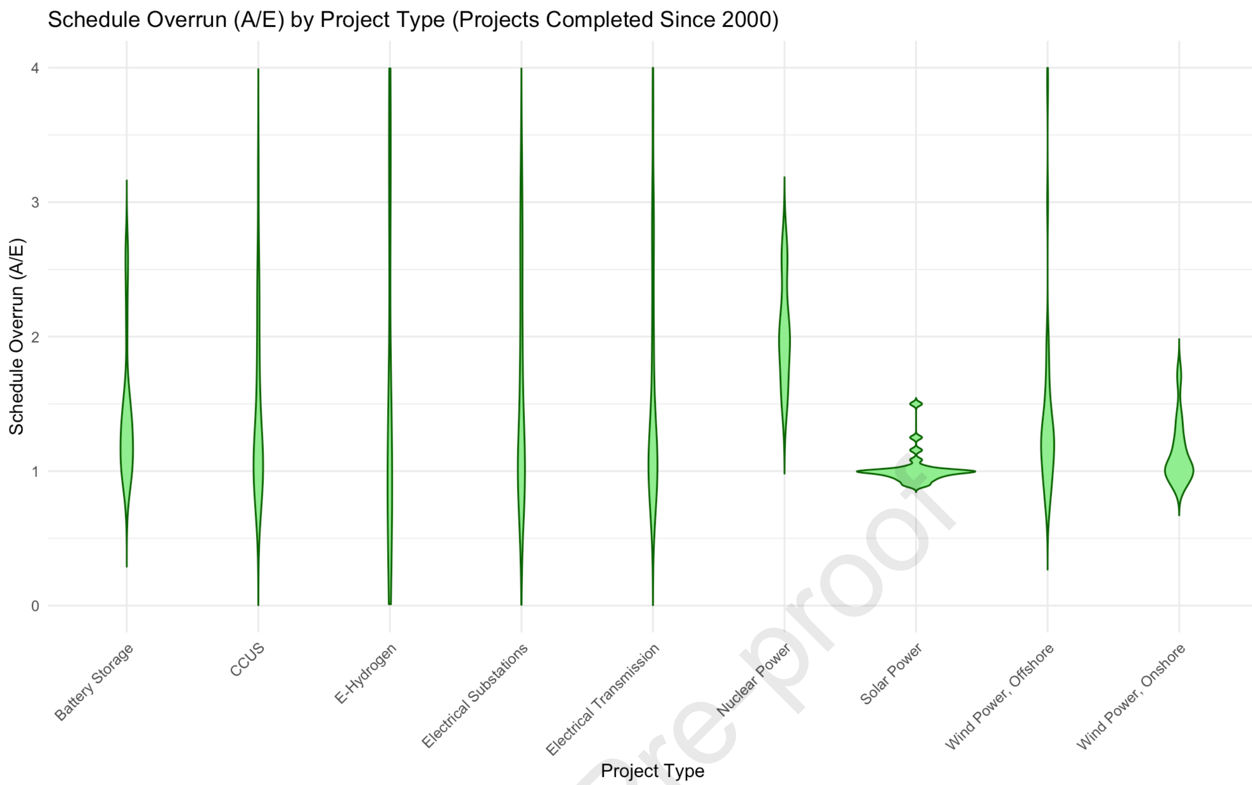
Color coded by number of responses	19-20	14-18	10-13	6-9	3-5	0-2



Cost Overrun (A/E) by Project Type
30.0
10.0
3.0
1.0
0.3
Cost Overrun (A/E)
Battery Storage
CCUS
E-Hydrogen
Electrical Substations
Electrical Transmission
Nuclear Power
Solar Power
Wind Power, Offshore
Wind Power, Onshore
Project Type


Schedule Overrun (A/E) by Project Type
10.0
1.0
0.1
Schedule Overrun (A/E)
Battery Storage
CCUS
E-Hydrogen
Electrical Substations
Electrical Transmission
Nuclear Power
Solar Power
Wind Power, Offshore
Wind Power, Onshore
Project Type


Cost Overrun (A/E) by Project Type (Projects Completed Since 2000)
Cost Overrun (A/E)
3
2
1
0
Battery Storage
CCUS
E-Hydrogen
Electrical Substations
Electrical Transmission
Nuclear Power
Solar Power
Wind Power, Offshore
Wind Power, Onshore
Project Type


Schedule Overrun (A/E) by Project Type (Projects Completed Since 2000)
Schedule Overrun (A/E)
0
1
2
3
4
Battery Storage
CCUS
E-Hydrogen
Electrical Substations
Electrical Transmission
Nuclear Power
Solar Power
Wind Power, Offshore
Wind Power, Onshore
Project Type

Highlights

- Capital discipline is key to assuring infrastructure projects deliver their intended performance
- Clean energy infrastructure projects display a history of cost overruns and delays
- Strong incentives encourage project developers to compromise on capital discipline
- Strengthened public institutions are needed to assure value through robust project oversight