# Princeton's Net-Zero America study
# Annex M: Mobilizing Capital for the Transition

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| **Acronyms** | |
|---|---|
| COD | Commercial Operating Date |
| FID | Final Investment Decision |
| FOAK | First-of-a-Kind |
| GDP | Gross Domestic Product |
| TIC | Total Investment Cost |

# 1 Introduction

The energy system models used in the *Net-Zero America* study (NZA) generate deep decarbonization pathways by minimizing total system costs expressed as net present value (NPV) over the transition period (e.g., 2020-2050). All scenarios are underpinned by assumptions about technology performance and costs over time, both of which become increasingly favorable over time, as each technology follows its respective learning curve. Alternate pathways are generated, in acknowledgement of the uncertainty around future costs and technology uptake, by imposing different constraints in relation to end use electrification and deployment of specific supply-side technologies. Consistent with other studies which adopt such approaches, the incremental NPV of the total system cost of Net-Zero America pathways relative to the reference case results in only a modest increase in energy service expenditures as a percentage of the nation's GDP, as illustrated in Figure 1.

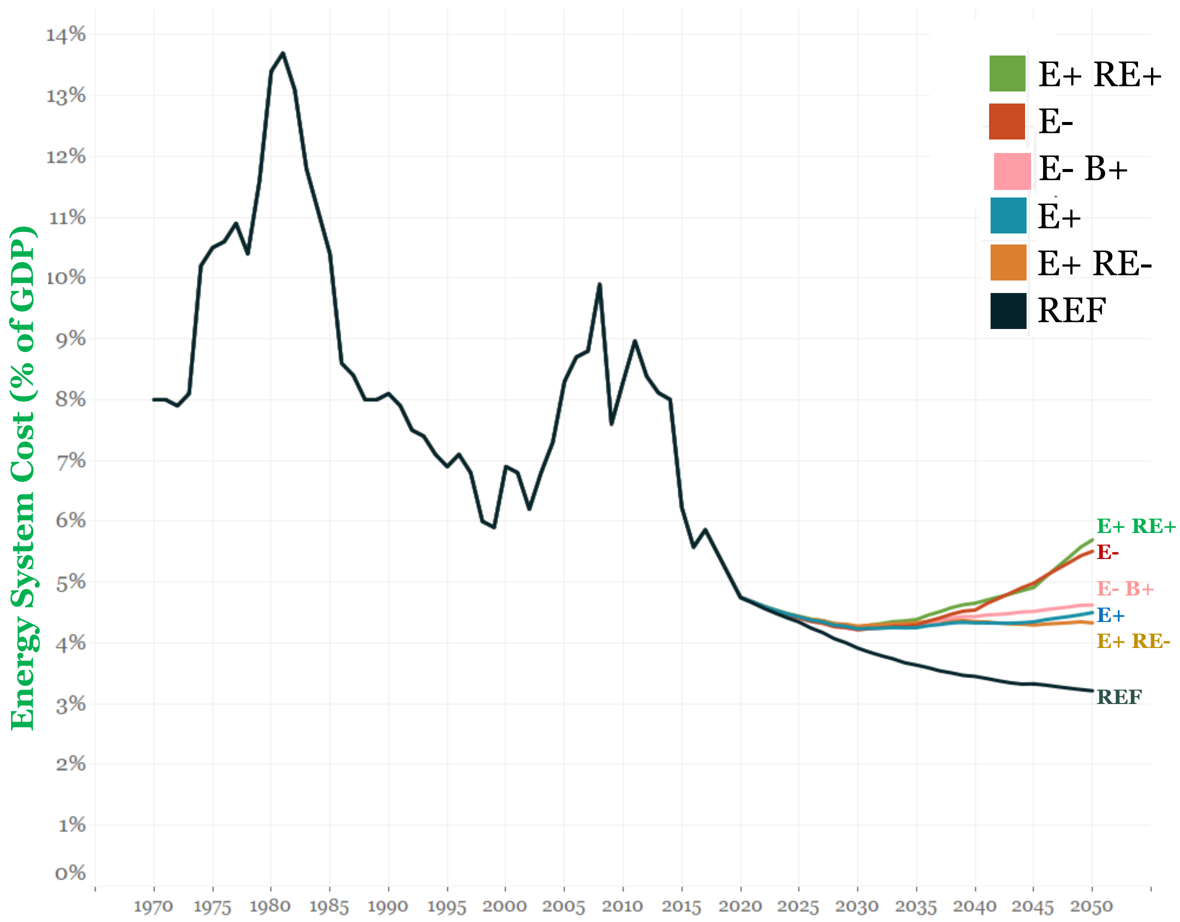


*Figure 1 Modeled annual energy-system costs as % of GDP are comparable to recent energy-system costs and around 1 to 2.5 percent of GDP more than the reference scenario by 2050. The modeling assumed the same low oil and gas prices for the net-zero and reference scenarios. Because demand for oil and gas is higher in the reference case, it is plausible that oil and gas prices would also be higher in that case. If that were so, the net-zero pathways depicted here could have lower annualized energy system costs than the reference case.*

The Net-Zero America transitions are also consistent with other studies illustrating that deep decarbonization pathways are fundamentally capital intensive, with higher system capital costs substituting for fuel and operating costs over time. Accordingly, a key benefit of most deep decarbonization pathways is a shift away from a dependence on fossil fuels and their ongoing costs (and price volatility), to essentially zero marginal cost renewable resources. Notwithstanding the benefits of the transition, there are challenges associated with the rapid mobilization of large sums of risk-capital implied in net-zero transitions.

The capital intensification trend for NZA scenarios is illustrated in Figure 2.

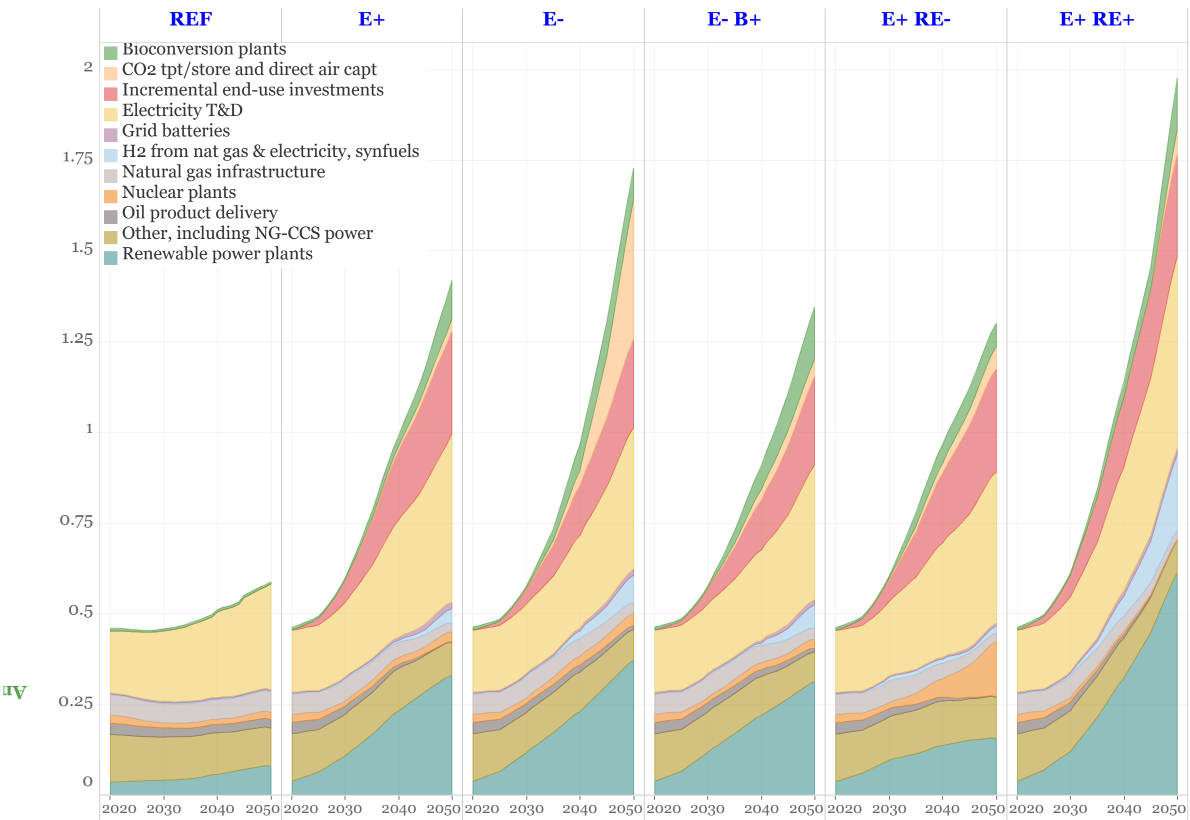


*Figure 2 Annualized capital related charges (including annualized principal, cost of capital, and fixed operating and maintenance costs), illustrates the capital-intensive nature of all Net Zero America scenario*

From the RIO model outputs, we are able to disaggregate the cumulative supply side capital in service over time for each of the core scenarios for key technologies – electricity generation, electricity transmission and distribution, and liquid and gaseous fuel production/conversion assets. In addition to these assets we include investment in $CO_2$ transport infrastructure as developed in Annex I. Figure 3 further illustrates the shift towards a more capital-intensive energy supply system in all of the net-zero pathways.

It is worth noting that we do not yet provide a comprehensive coverage of the total transition investment capital. On the supply side, we specifically exclude liquid and gaseous fuel distribution infrastructure. These comprise a diverse range of assets from major pipelines to long-haul freight assets to refueling stations. We expect very significant investments will be needed for fuels logistics systems across all net-zero pathways, which will increase the differential capital relative to the Reference scenario. We also have not dealt in detail with the very significant demand-side investments in buildings, transport, industrial decarbonization measures other than cement and steel, efficiency improvements and establishment of bioenergy crops.

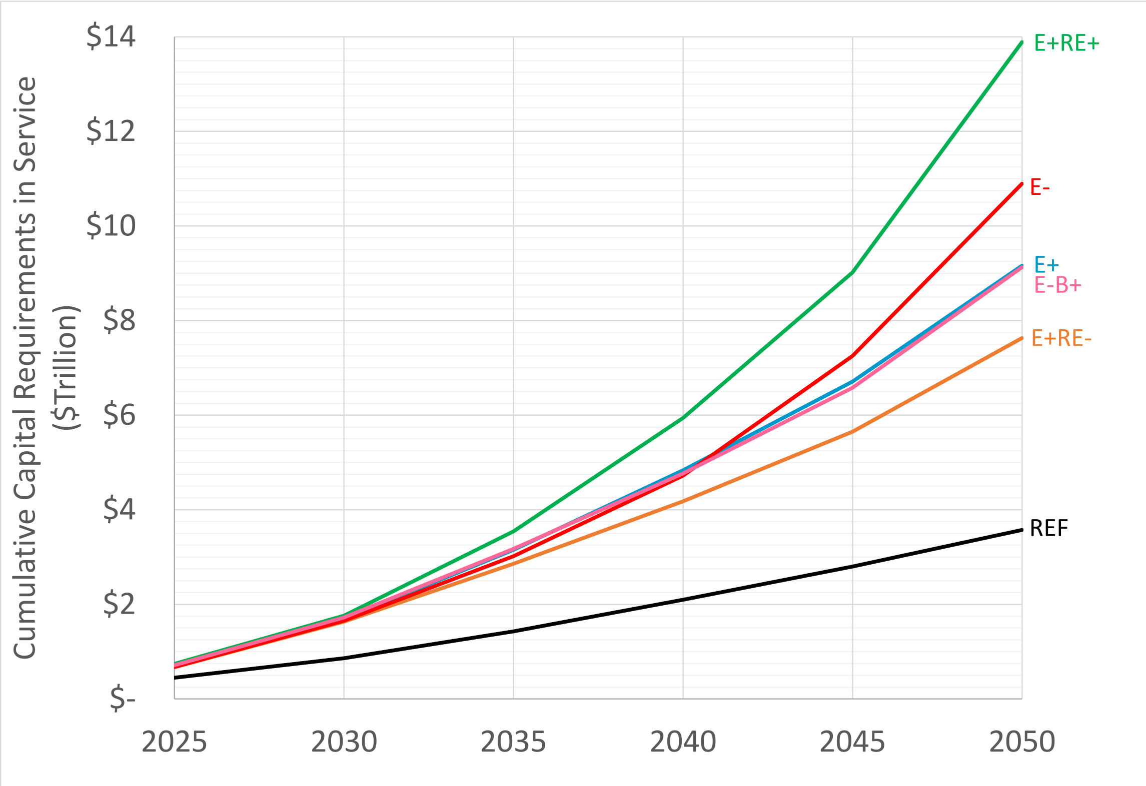


*Figure 3 Cumulative capital in service for zero-carbon energy supply assets and infrastructure over time in NZA pathways relative to a business-as-usual Reference case. Energy supply assets include power generation, transmission and distribution, fuels conversion assets and $CO_2$ transport infrastructure.*

In this work we seek to explore further the challenge of mobilizing this investment capital for the main energy-supply technologies and associated infrastructure, focusing on the E+ scenario. The main purpose of this analysis is to draw attention to the very significant task of mobilizing investment capital.

## 2 Limitations of Energy System Modelling Approach

The energy system models used for the *Net-Zero America* study, like many such optimization-based decarbonization modeling approaches, are characterized by a high degree of foresight and seamless integration between sectors. Such characteristics are a highly idealized representation of the real world in which low-carbon energy investment decisions are made. The investor's world is characterized by deep uncertainty around future technology costs and performance, policy priorities of future governments, investment preferences among peers, customers and competitors, and public acceptance of certain technologies. Furthermore, while models readily capture opportunities to integrate energy supplies and demands across different sectors, these opportunities are rarely captured by investors and operators in different sectors due to a lack of visibility across sectors, different capabilities and risk profiles among different sectors, and transaction costs associated with realizing the benefits of coordination across sectors.

Energy transition models also assume a rational and efficient market that sees investors respond instantly to market signals to mobilize capital overnight. In reality, capital is mobilized through a sequence of decisions and activities which consume considerable resources and require significant lead times.

The gaps between modeling assumptions of Net-Zero America pathways and the real world of investment decisions obscure a number of potential challenges and transition bottlenecks associated with the increased demand for risk-capital for project development and greenfield construction.

# 3 Capital sources and risk

The United States is the world's largest national economy and financial capital is generally considered abundant, with a large quantum of available funds in:

- Debt (& bond) markets - funds that are fully repayable to a schedule, ahead of returns to equity investors; and
- 'Funds under management' or equity invested in private equity, sovereign wealth funds, pension funds, hedge funds, infrastructure funds, etc.

Notwithstanding the apparent abundance of capital to service Net-Zero America transitions, capital mobilization is a challenge, because the availability and risk appetite of different classes of capital is heterogenous. Debt funds are generally more risk-averse and lower-cost than equity funds, and different categories of equity funds also target different levels of risk and return.

Debt funds will generally require a very high level of assurance that net revenues from a project are, or will be, sufficient to cover scheduled periodic repayments of interest and principal with a safety margin (debt service coverage ratio). They will also often require a priority security over the project assets for low-risk investments, and/or to be guaranteed by corporate balance sheets for higher-risk projects.

The majority of (equity) funds under management target liquid investments with existing, predictable cashflows; just a fraction is invested in fixed long-term plant and infrastructure assets, and an even smaller fraction invested in greenfield project development & construction investments (risk-capital).

In this report, the term 'risk-capital' refers to sums of capital committed prior to Commercial Operation Date (COD) of projects, the point in time in which a project completes commissioning (often with a formal Performance Acceptance Test), begins commercial sales and generates revenue. These sums are exposed to various completion risks—development, market, project construction and performance risks which could impact project cashflows and hence project valuation. These risks tend to limit the availability, and increase the cost, of investment capital. In many cases, especially where project proponents have a limited track record, or there are perceived risks around technology novelty, construction risk, or off-take risk—e.g. lack of a power purchase agreement (PPA)—debt funders and many categories of equity funds will typically avoid investment until after commercial operations are achieved.

In all cases, projects will be developed according to a decision sequence through which investors seek to progressively mitigate the risks and uncertainties and to maximize confidence in an investment. Each stage in the sequence consumes resources, time and capital.

# 4 Investment Decision Sequence

Project developers typically follow an investment decision sequence (or project value assurance process) in which projects are progressively de-risked (1) (2). This involves a gradually increasing level of investment of 'at-risk' capital to support a range of multi-disciplinary studies, multi-stakeholder engagement activities and project planning to reduce uncertainty, mitigate risks and increase confidence in the estimated value to be created by the project.

As shown in Figure 4, the decision sequence is typically stage-gated, meaning the development would typically not proceed from one phase to the next without repeated, rigorous reassessments of the project risks and estimated project value. At each decision gate, the investor can decide to continue (to the next stage), pause or abandon the project, or to recycle the project (repeat the prior stage with a different configuration).

The final investment decision (FID) comes when the project developer has demonstrated an acceptable level of confidence in the project valuation to support a much larger investment in the design, construction and commissioning of the project. That means the developer and co-investors have been satisfied that the technical, 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.

The decision sequence leading up to FID can be of the order of months to a decade or more, and will generally require an investment by the developer of some percentage of the total investment capital (TIC). The actual pre-FID investment lead time and demands on capital will be a function of the project's scale, value and complexity, and the risk appetite of the developer and/or any co-investors or lenders of capital for the project. This pre-FID investment is fully 'at-risk' because there is no certainty that the project will proceed to a point where the investment is recoverable through operating profits or divestment. Accordingly, it is typically funded by the developer's own equity.

FID signals a significant reduction in risk, attracting a broader range of capital sources to support a much larger investment in design, construction, and commissioning to bring the project into commercial operation. However, the project retains significant greenfield construction and technology performance risk and so precludes a significant volume of potential capital sources (both debt and equity) at this stage.

Reaching COD, typically formally through a successful Performance Acceptance Test, signals a major reduction in the project risk profile, with the project having essentially overcome all construction and most technology performance risks[1] and verified the capacity to earns profits. This provides the necessary evidence to verify the project valuation and expands the availability and lowers the cost of investment capital, allowing developers to reduce their stake for a profit.

[1] Residual risks may persist after COD associated with the longer-term performance of equipment and natural resources (e.g. $CO_2$ storage reservoirs), especially with novel technologies.

# 5 Investment decision sequence: estimates of time and cost

## 5.1 Scope of Pre-FID Activities

The range of Pre-FID studies, planning activities and negotiations that will typically be undertaken as part of the investment decision sequence is extensive and serves to provide confidence to the developer, co-investors, lenders, regulators and various other stakeholders that the project will deliver the intended value, safely and in compliance with mandated environmental and social standards.

Such studies and activities may include, without being limited to:

- Engineering, logistics and cost estimating;
- Resource characterization;
- Site evaluation and selection;
- Environmental and social impact assessments;
- Site access and right-of-way agreements;
- Procurement agreements for supply of goods and services necessary to sustain operations;
- Market analysis and offtake agreements;
- Development of operational management plans;
- Engineering, Procurement and Construction contract negotiations for delivery of facilities;
- Project permitting and securing necessary licenses; and
- Comprehensive risk assessments including mitigation and contingency planning.

As the project proceeds through each stage from left to right in Figure 4, the time and the amount of investment required typically increases, while the residual risk and uncertainty reduces. Best practice would typically involve the same broad nature of studies and activities to be undertaken—being more conceptual and indicative in nature at the scoping study, and becoming increasingly project- and site-specific, detailed, accurate and robust, during the prefeasibility and feasibility studies.

It is also worth noting that not every proposal will proceed to FID. It is usual for a percentage of projects to be abandoned or recycled back to a prior stage as they progress along the investment decision sequence. Accordingly, a developer's portfolio will feature a declining number of project proposals moving from left to right along the decision sequence shown in Figure 4.

At FID, developers will also need to satisfy potential co-investors that all of the necessary capital is available to take the project to COD. This means the developer will require funding agreements in place with all equity and debt providers before the first drawdown can be made. This execution of all of the funding agreements, potentially with some conditions-precedent in place, is often called Financial Close, at which point FID is confirmed.

Depending on the scale, complexity and risk profile of the project, the number of equity and debt providers could range from just one or two, to more than 20 organizations. A lead financial institution will usually be appointed to manage the negotiation and completion of funding agreements and may commission a number of independent expert reviews to verify the developer's analysis and findings, for which a separate upfront finance fee may be charged.

## 5.2 Project Capital Costs

The methods and results for developing deployment schedules and capital cost estimates for the deployment of energy generation plant and supporting infrastructure over time are variously described in other Annexes to the *Net-Zero America* interim report: A. Evolved Energy Research final report; D. Siting solar and wind generation; E. Siting electricity transmission; F. Siting thermal power plants; G. Siting bioconversion facilities; H. Sizing and siting CO2 pipelines; I. Iron and steel industry scenario; J. Cement industry scenario; and K. Hydrogen supply infrastructure. These annexes essentially define the temporal and spatial deployment in terms of capacity additions for each technology reaching COD, in 5-year time steps from 2020 to 2050.

In this Annex we use the results of those analyses to estimate annual and cumulative capital expenditure by sector and technology in real terms over the transition. These capital expenditures incorporate assumed 'learning-curve' cost reductions over time, but exclude pre-FID development costs and any early-mover cost premiums that might be experienced for technologies not recently demonstrated or deployed at large scale in the United States. These excluded costs are estimated here separately, as discussed in the next two sections.

## 5.3 Estimates of time and cost of pre-FID activities

Section 5.1 illustrates the extensive and comprehensive range of activities that would typically be undertaken in support of the capital investment decision process. The cost and timeframes for such activities can vary enormously, as will the percentage of proposals which actually pass through each decision gate. For the purposes of this work, we estimated generic values for each technology and infrastructure type through each phase of the decision sequence. These generic estimates (Table 1, Table 2, Table 3, and Table 4) are based on one of the author's[2] more than 20 years of project development and management experience. If the capital mobilization challenge for Net-Zero America is to be explored more deeply, these generic estimates should be validated through expert elicitation involving developers, contractors and investors currently active in the development of each technology and infrastructure type in the United States.

In these tables, Pre-FID Cost (% of TIC) [column 3 in the first table for each sector] is calculated as the sum of the quotient of cost per study and success rate for each of the phases. Total Pre-FID Cost is then that calculated as Pre-FID Cost plus the Financing Costs. This total represents the *effective* investment in pre-FID activities for projects actually passing FID. It is worth noting that we assume that no projects which pass FID and begin construction, fail to achieve COD and operate for their intended life.

[2] Chris Greig led several companies developing green- and brown-fields projects the agri-food, resources and energy sectors, mainly in the Asia-Pacific region, over a 25-year career before joining academia.

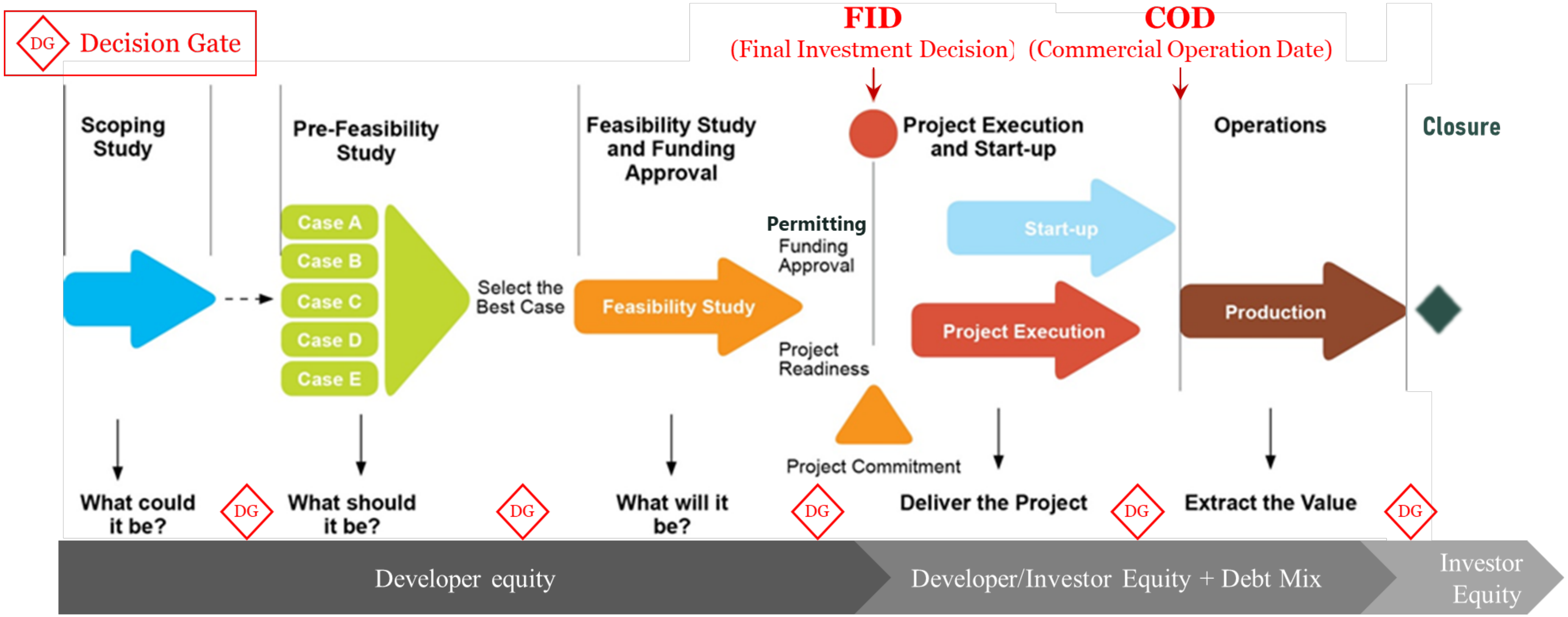


*Figure 4 Generic Project Lifecycle – A stage-gated decision sequence sees a gradual increase in investment of 'at-risk' capital, punctuated by a number of interim Decision Gates. Activities prior to FID include those to progressively reduce the risks and uncertainties to the point where there is sufficient confidence in the likely project value to take FID: project planning; multidisciplinary studies; site evaluation and selection; market analysis; negotiation of various contracts for the supply of goods and services along with off-take, permitting, and financing agreements. At FID, a much larger investment is authorized to support the design, construction, and commissioning of the facilities and to bring the project into commercial operation. COD will typically be formalized after a Performance Acceptance Test and signals a major reduction in the project risk profile.*

*Graphic based on Figure 3 in W. Mackenzie and N. Cusworth, "The use and abuse of feasibility studies," in Proceedings Project Evaluation 2007, pp 65-76, The Australasian Institute of Mining and Metallurgy, Melbourne, 2007.*

*Table 1 Estimates of times, costs and success rates associated with the investment decision sequence for the power sector.*

**POWER SECTOR**

**Generation**

| Technology | Pre-FID Time (years) | PreFID Cost[1] (% of TIC) | Financing Cost[2] (% of TIC) | Total Pre-FID Cost (% of TIC) | Financial Close (years) | Construction Time (years) FID to COD | Overall Dev Time (years) Concept to COD |
|---|---|---|---|---|---|---|---|
| biomass w cc | 2.5 | 9.0% | 1.5% | 10.5% | 0.5 | 4 | 7 |
| CCGT | 1 | 4.5% | 1.0% | 5.5% | 0.5 | 2 | 3.5 |
| CCGT w CC | 2.5 | 9.0% | 1.5% | 10.5% | 0.5 | 4 | 7 |
| CT | 1 | 4.5% | 1.0% | 5.5% | 0.5 | 1 | 2.5 |
| geothermal | 2 | 9.0% | 1.0% | 10.0% | 0.5 | 2 | 4.5 |
| nuclear | 5 | 24.1% | 3.0% | 27.1% | 1 | 5 | 11 |
| offshore wind | 2.5 | 10.0% | 1.5% | 11.5% | 0.5 | 3 | 6 |
| onshore wind | 1.5 | 5.5% | 1.0% | 6.5% | 0.5 | 2 | 4 |
| solar pv | 1 | 5.5% | 1.0% | 6.5% | 0.5 | 1 | 2.5 |
| storage li-ion | 1 | 4.5% | 1.0% | 5.5% | 0.5 | 1 | 2.5 |

[2] Upfront project finance fee charged by lead bank

[1]Calculated as follows

| Technology | Cost per study (% of TIC) | | | Success Rate | | | |
|---|---|---|---|---|---|---|---|
| | Scoping Study | Prefeasibility | Feasibility | Scoping Study | Prefeasibility | Feasibility | Cost per Projec |
| biomass w cc | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9.0% |
| CCGT | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 4.5% |
| CCGT w CC | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9.0% |
| CT | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 4.5% |
| geothermal | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9.0% |
| nuclear | 1.00% | 2.00% | 4% | 10% | 33% | 50% | 24.1% |
| offshore wind | 0.30% | 1.00% | 2% | 10% | 33% | 50% | 10.0% |
| onshore wind | 0.20% | 0.50% | 1% | 10% | 33% | 50% | 5.5% |
| solar pv | 0.20% | 0.50% | 1% | 10% | 33% | 50% | 5.5% |
| storage li-ion | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 4.5% |

**Transmission**

| Technology | Pre-FID Time (years) | PreFID Cost[1] (% of TIC) | Financing Cost[2] (% of TIC) | Total Pre-FID Cost (% of TIC) | Financial Close (years) | Construction Time (years) FID to COD | Overall Dev Time (years) Concept to COD |
|---|---|---|---|---|---|---|---|
| MSA to MSA | 5 | 16.1% | 1.0% | 17.1% | 1 | 4 | 10 |
| Transmission Assets (average) | 2.5 | 5.7% | 1.0% | 6.7% | 0.5 | 4 | 7 |
| Spur Lines (Onshore) | 1.5 | 2.8% | 1.0% | 3.8% | 0.5 | 4 | 6 |
| Spur Lines (Offshore) | 2.5 | 5.7% | 1.0% | 6.7% | 0.5 | 4 | 7 |
| Sustaining Capital | 0.5 | 1.0% | 0.0% | 1.0% | 0.5 | 1 | 2 |

[2] Upfront project finance fee charged by lead bank

[1]Calculated as follows

| Technology | Cost per study (% of TIC) | | | Success Rate | | | |
|---|---|---|---|---|---|---|---|
| | Scoping Study | Prefeasibility | Feasibility | Scoping Study | Prefeasibility | Feasibility | Cost per Projec |
| MSA to MSA | 0.20% | 2.00% | 4% | 10% | 33% | 50% | 16.1% |
| Transmission Assets (average) | 0.20% | 1.00% | 2% | 20% | 50% | 75% | 5.7% |
| Spur Lines (Onshore) | 0.10% | 0.50% | 1% | 20% | 50% | 75% | 2.8% |
| Spur Lines (Offshore) | 0.20% | 1.00% | 2% | 20% | 50% | 75% | 5.7% |
| Sustaining Capital | | | 1% | 100% | 100% | 100% | 1.0% |

**Distribution Networks**

| Technology | Pre-FID Time (years) | PreFID Cost[1] (% of TIC) | Financing Cost[2] (% of TIC) | Total Pre-FID Cost (% of TIC) | Financial Close (years) | Construction Time (years) FID to COD | Overall Dev Time (years) Concept to COD |
|---|---|---|---|---|---|---|---|
| Distribution Assets | 1 | 2.5% | 0.5% | 3.0% | 0.5 | 1 | 2.5 |
| Sustaining Capital | 1 | 1.0% | 0.5% | 1.5% | 0.5 | 1 | 2.5 |

[2] Upfront project finance fee charged by lead bank

[1]Calculated as follows

| Technology | Cost per study (% of TIC) | | | Success Rate | | | |
|---|---|---|---|---|---|---|---|
| | Scoping Study | Prefeasibility | Feasibility | Scoping Study | Prefeasibility | Feasibility | Cost per Projec |
| Distribution Assets | 0.10% | 0.50% | 1% | 20% | 50% | 100% | 2.5% |
| Sustaining Capital | | | 1% | 100% | 100% | 100% | 1.0% |

*Table 2 Estimates of times, costs and success rates associated with the investment decision sequence for the fuels conversion sector*

**Fuels Convesrsion**

| Technology | Pre-FID Time (years) | PreFID Cost[1] (% of TIC) | Financing Cost[2] (% of TIC) | Total Pre-FID Cost (% of TIC) | Financial Close (years) | Construction Time (years) FID to COD | Overall Dev Time (years) Concept to COD |
|---|---|---|---|---|---|---|---|
| Autothermal CH4 reforming | 2 | 4.5% | 1.0% | 5.5% | 1 | 2 | 5 |
| Autothermal CH4 reforming with CCU | 2 | 9.0% | 1.5% | 10.5% | 2 | 3 | 7 |
| BECCS Hydrogen | 2 | 9.0% | 1.0% | 10.0% | 2 | 4 | 8 |
| Biomass to Syngas | 2 | 9.0% | 1.5% | 10.5% | 2 | 3 | 7 |
| Biomass to Syngas with CCU | 2 | 9.0% | 1.0% | 10.0% | 2 | 4 | 8 |
| Biomass FT to Diesel | 2 | 9.0% | 1.0% | 10.0% | 2 | 3 | 7 |
| Biomass FT to Diesel with CCU | 2 | 9.0% | 3.0% | 12.0% | 2 | 4 | 8 |
| Biomass Pyrolysis | 2 | 4.5% | 1.5% | 6.0% | 2 | 3 | 7 |
| Biomass Pyrolysis with CCU | 2 | 9.0% | 1.0% | 10.0% | 2 | 4 | 8 |
| Electrolyis | 2 | 4.5% | 1.0% | 5.5% | 1 | 2 | 5 |
| Direct Air Capture of CO2 | 2 | 9.0% | 1.0% | 10.0% | 1 | 2 | 5 |
| Electric Boiler | 2 | 9.0% | 1.0% | 10.0% | 2 | 1 | 5 |
| Hydrogen Blend | 1 | 4.5% | 1.0% | 5.5% | 1 | 1 | 3 |
| Industrial Hydrogen Boiler | 2 | 4.5% | 1.0% | 5.5% | 1 | 2 | 5 |
| Industrial Pipeline Gas Boiler | 2 | 4.5% | 1.0% | 5.5% | 1 | 1 | 4 |
| Liquids synthesis from H2 & CO2 | 2 | 9.0% | 1.0% | 10.0% | 1.5 | 3 | 6.5 |
| Methane synthesis form H2 & CO2 | 2 | 9.0% | 1.0% | 10.0% | 1.5 | 3 | 6.5 |

[2] Upfront project finance fee charged by lead bank

[1]Calculated as follows

| Technology | Cost per study (% of TIC) | | | Success Rate | | | Cost per Projec |
|---|---|---|---|---|---|---|---|
| | Scoping Study | Prefeasibility | Feasibility | Scoping Study | Prefeasibility | Feasibility | |
| Autothermal CH4 reforming | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 5% |
| Autothermal CH4 reforming with CCU | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| BECCS Hydrogen | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Biomass to Syngas | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Biomass to Syngas with CCU | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Biomass FT to Diesel | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Biomass FT to Diesel with CCU | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Biomass Pyrolysis | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 5% |
| Biomass Pyrolysis with CCU | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Electrolyis | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 5% |
| Direct Air Capture of CO2 | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Electric Boiler | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Hydrogen Blend | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 5% |
| Industrial Hydrogen Boiler | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 5% |
| Industrial Pipeline Gas Boiler | 0.10% | 0.50% | 1% | 10% | 33% | 50% | 5% |
| Liquids synthesis from H2 & CO2 | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |
| Methane synthesis form H2 & CO2 | 0.20% | 1.00% | 2% | 10% | 33% | 50% | 9% |

*Table 3 Estimates of times, costs and success rates associated with the investment decision sequence for $CO_2$ transport & storage assets*

**CO2 Pipeline Network**

| Technology | Pre-FID Time (years) | PreFID Cost[1] (% of TIC) | Financing Cost[2] (% of TIC) | Total Pre-FID Cost (% of TIC) | Financial Close (years) | Construction Time (years) FID to COD | Overall Dev Time (years) Concept to COD |
|---|---|---|---|---|---|---|---|
| Inter-Regional Trunk Lines | 5 | 13.0% | 1.5% | 14.5% | 1 | 5 | 11 |
| Spur Lines | 2.5 | 4.2% | 1.0% | 5.2% | 0.5 | 3 | 6 |
| E&A, Wells & Facilities | 1 | 5.0% | 0.0% | 5.0% | 0 | 1 | 2 |

[2] Upfront project finance fee charged by lead bank

[1]Calculated as follows

| Technology | Cost per study (% of TIC) | | | Success Rate | | | Cost per Projec |
|---|---|---|---|---|---|---|---|
| | Scoping Study | Prefeasibility | Feasibility | Scoping Study | Prefeasibility | Feasibility | |
| Inter-Regional Trunk Lines | 0.20% | 1.00% | 4% | 10% | 33% | 50% | 13% |
| Spur Lines | 0.10% | 0.50% | 2% | 20% | 50% | 75% | 4% |

*Table 4 Estimates of times, costs and success rates associated with the investment decision sequence for example industries in industry sector*

**INDUSTRY**

| Technology | Pre-FID Time (years) | PreFID Cost[1] (% of TIC) | Financing Cost[2] (% of TIC) | Total Pre-FID Cost (% of TIC) | Financial Close (years) | Construction Time (years) FID to COD | Overall Dev Time (years) Concept to COD |
|---|---|---|---|---|---|---|---|
| Cement | 2.5 | 4.2% | 1.0% | 5.2% | 0.5 | 4 | 7 |
| Steel | 2.5 | 4.2% | 1.0% | 5.2% | 0.5 | 3 | 6 |

[2] Upfront project finance fee charged by lead bank

[1]Calculated as follows

| Technology | Cost per study (% of TIC) | | | Success Rate | | | |
|---|---|---|---|---|---|---|---|
| | Scoping Study | Prefeasibility | Feasibility | Scoping Study | Prefeasibility | Feasibility | Cost per Projec |
| Cement | 0.10% | 0.50% | 2% | 20% | 50% | 75% | 4% |
| Steel | 0.10% | 0.50% | 2% | 20% | 50% | 75% | 4% |

## 5.4 First-of-a-kind (FOAK) Demonstration Estimates

All technologies deployed in the *Net-Zero America* study have been demonstrated at pilot or industrial scale, somewhere in the world. Furthermore, all of the technologies in Net-Zero America scenarios that expand significantly during the first decade are already being deployed at scale in the United States. These technologies, like wind and solar generation, natural gas power generation, and natural gas reforming are mature and assumed to be following cost-reduction trajectories documented in other annexures.

However, a number of the technologies which are expected to expand after 2030, have seen limited or no recent demonstration and deployment at large scale in the United States. Commercial deployment of these technologies is likely to experience some first-of-a-kind or early-mover challenges, including construction cost premiums, construction time delays, start-up challenges and operating performance shortfalls (2). It is therefore prudent to expect an investment capital premium on the first few demonstrations for such technologies.

Technologies for which FOAK demonstrations are suggested by the Net-Zero America modelling results for the 2020's include:

Power Sector:

- Advanced Nuclear
- CCGT with $CO_2$ capture (post-combustion capture)
- CCGT with $CO_2$ capture (oxyfuel, including Allam-cycle)
- Biomass Gasification Power with $CO_2$ capture
- High H2 Turbines (for combined cycle and combustion turbine power plants)
- Advanced Geothermal

Fuels Sector:

- Methane Autothermal Reforming (ATR) H2 with $CO_2$ capture
- Biomass Gasification H2 with $CO_2$ capture
- Biomass Pyrolysis
- Electrolysis
- Direct Air Capture

Industry

- Cement with $CO_2$ capture
- Direct Reduction Iron

Based on (3), we have applied notional premiums of up to 150% of reference overnight capital costs across Pre-FID, design, construction and commissioning on up to five first-N-of-a-kind commercial projects. Where the technology is not deployed before 2035 in E+ and or is not required by multiple scenarios, we arbitrarily reduced the number of commercial projects to be supported to three (Advanced Geothermal) or four (Advanced Nuclear). The FOAK multiplier on the assumed technology costs used in the models was set at 2.5 and is a notional estimate based on the author's judgement and analysis of a number of early-mover energy sector projects (3). The FOAK project allowances for the various technologies are shown in Table 5. Overall $137 billion was estimated for FOAK projects from 2021 to 2030.

*Table 5 Estimated capital costs for first-N-of-a-kind (FOAK) commercial projects to be undertaken by 2030.*

| Technology | Capacity/Project | Units | No of Projects | Mature Technology Cost assumed in Model | FOAK Multiplier (inclusive of Pre-FID) | Total FOAK Projects Investment ($.M) |
|---|---|---|---|---|---|---|
| **Power** | | | 27 | | | |
| Advanced Nuclear | 300 | MW | 4 | $ 6,465 per kW | 2.5 | $ 19.4 |
| CCGT with CC | 300 | MW | 5 | $ 2,176 per kW | 2.5 | $ 8.2 |
| CCGT with CC (Oxy) | 300 | MW | 5 | $ 1,924 per kW | 2.5 | $ 7.2 |
| Biomass Gasification Power with CC | 300 | MW | 5 | $ 6,338 per kW | 2.5 | $ 23.8 |
| High H2 Turbines | 100 | MW | 5 | $ 520 per kW | 2.5 | $ 0.7 |
| Advanced Geothermal | 100 | MW | 3 | $ 5,472 per kW | 2.5 | $ 4.1 |
| **Fuels** | | | 30 | | | |
| ATR Hydrogen with CC | 300 | MW | 5 | $ 782 per kW | 2.5 | $ 2.9 |
| Biomass Gasification H2 with CC | 300 | MW | 5 | $ 2,599 per kW | 2.5 | $ 9.7 |
| Biomass Pyrolysis | 100 | MW | 5 | $ 3,991 per kW | 2.5 | $ 5.0 |
| Electrolysis | 100 | MW | 10 | $ 1,790 per kW | 2.5 | $ 4.5 |
| Direct Air Capture | 100,000 | TPA | 5 | $ 18,954,000 per tph $CO_2$ | 2.5 | $ 2.7 |
| **Industry** | | | 10 | | | |
| Cement with CC | 2.8 | MTPA | 5 | $ 3,500,000,000 per plant | 2.5 | $ 43.8 |
| DRI Iron | 2.25 | MTPA | 5 | $ 400,000,000 per plant | 2.5 | $ 5.0 |
| **TOTAL** | | | 67 | | | **$ 137** |

# 6 Capital Mobilization Schedules

The capital mobilization schedules for the energy-supply and key industrial projects, from 2020 through 2050, delineated above are summarized in Figure 5 (circa $10 trillion Total Invested Capital including Pre-FID studies, FOAK projects and project capital costs). The importance of the electricity sector is evident with over 85% of the capital allocated to electricity generation, transmission and distribution.

In Figure 5 we distinguish between capital that has been completed and in-service and capital that is committed and under construction. The TIC for any project is assumed to be fully committed at the time of FID, in advance of when the project comes into service by the estimated Construction Times given for each technology in Table 1 to Table 4.

Figure 6 shows the Pre-FID portion of these costs, circa $600 billion, broken out by sector. Pre-FID costs are assumed to be committed in advance of the in-service date, by the Total Development Times for each technology as given in Table 1 to Table 4.

The supply-side capital[3] requirements of $2.6 trillion to be mobilized in the 2020's is shown in Figure 7, with pre-FID costs of circa $190 billion broken out in Figure 8. Again, the electricity sector dominance is notable, comprising 80% of the total supply-side committed capital during the first decade.

[3] In addition to supply-side capital, each scenario also requires substantial incremental investment in demand-side assets including buildings, heating ventilation and cooling, appliances, lighting, and vehicles. These are estimated in Section 7, but we do not assume any estimate pre-FID capital required for these investments. Many are consumer decisions that typically do no involve significant pre-FID capital (e.g. personal vehicle or appliance purchases), but some categories of demand-side investments may require additional pre-FID capital mobilization not considered herein (e.g. buildings and industrial process efficiency).

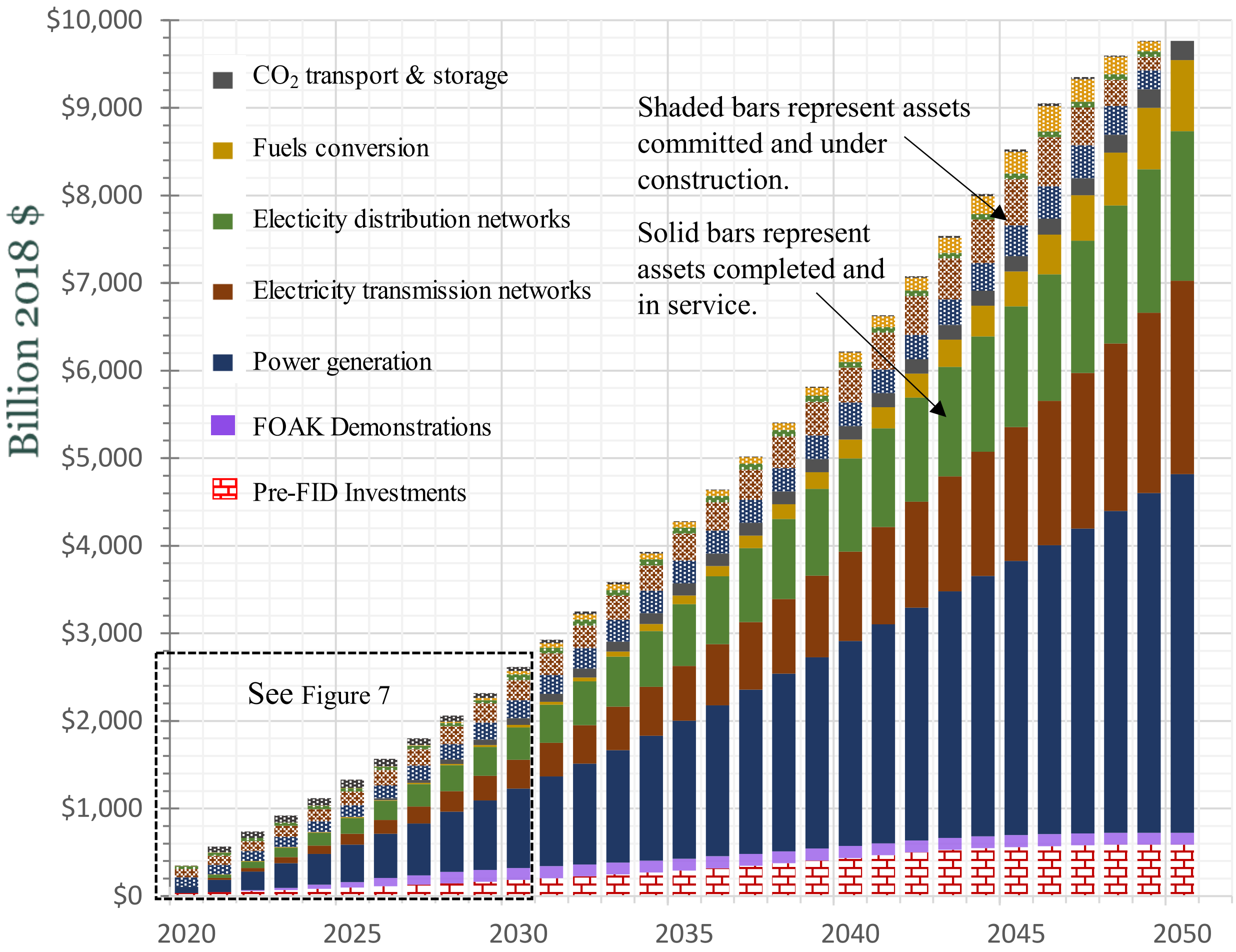


*Figure 5 Estimates of cumulative capital mobilization of almost $10 trillion for supply-side investments from 2020 to 2050 by sector (including Pre-FID at-risk capital). Solid bars indicate capital projects built and in service, while shaded parts of the bars indicate capital that has been committed and is still under construction.*

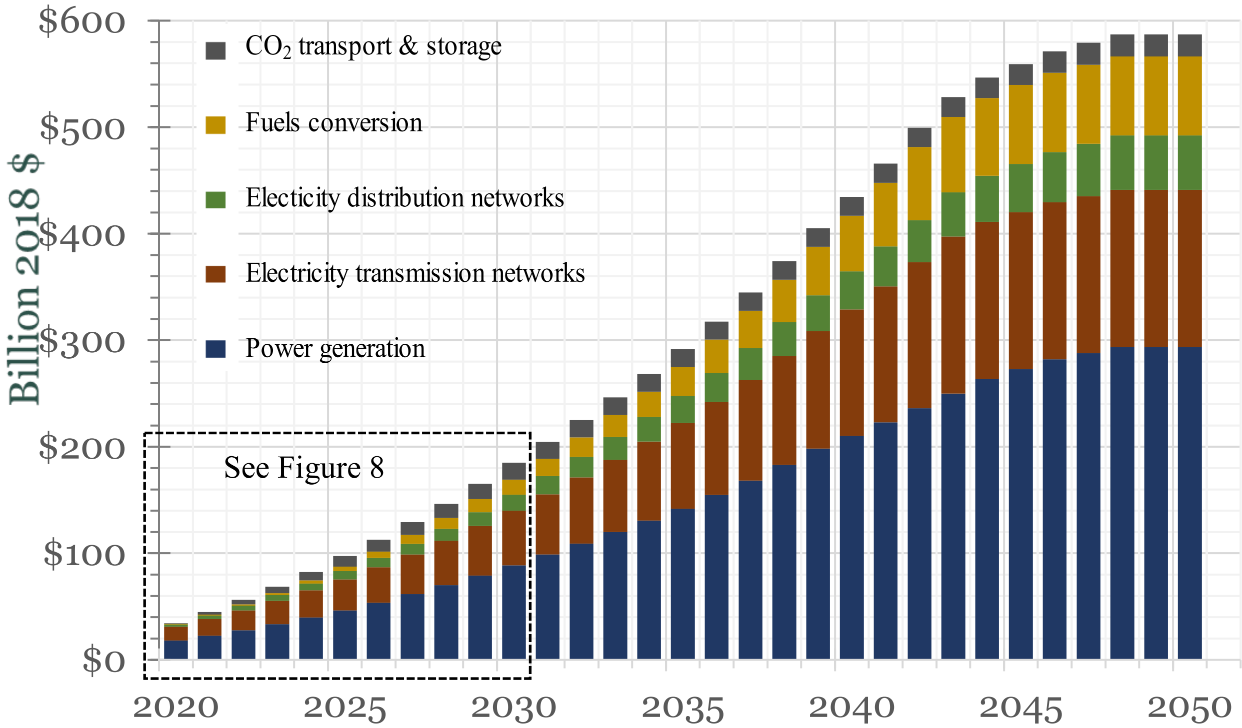


*Figure 6 Estimated cumulative 2020 – 2050 at-risk pre-FID investment, circa $600 Billion, required to enable investment capital mobilization depicted in Figure 5*

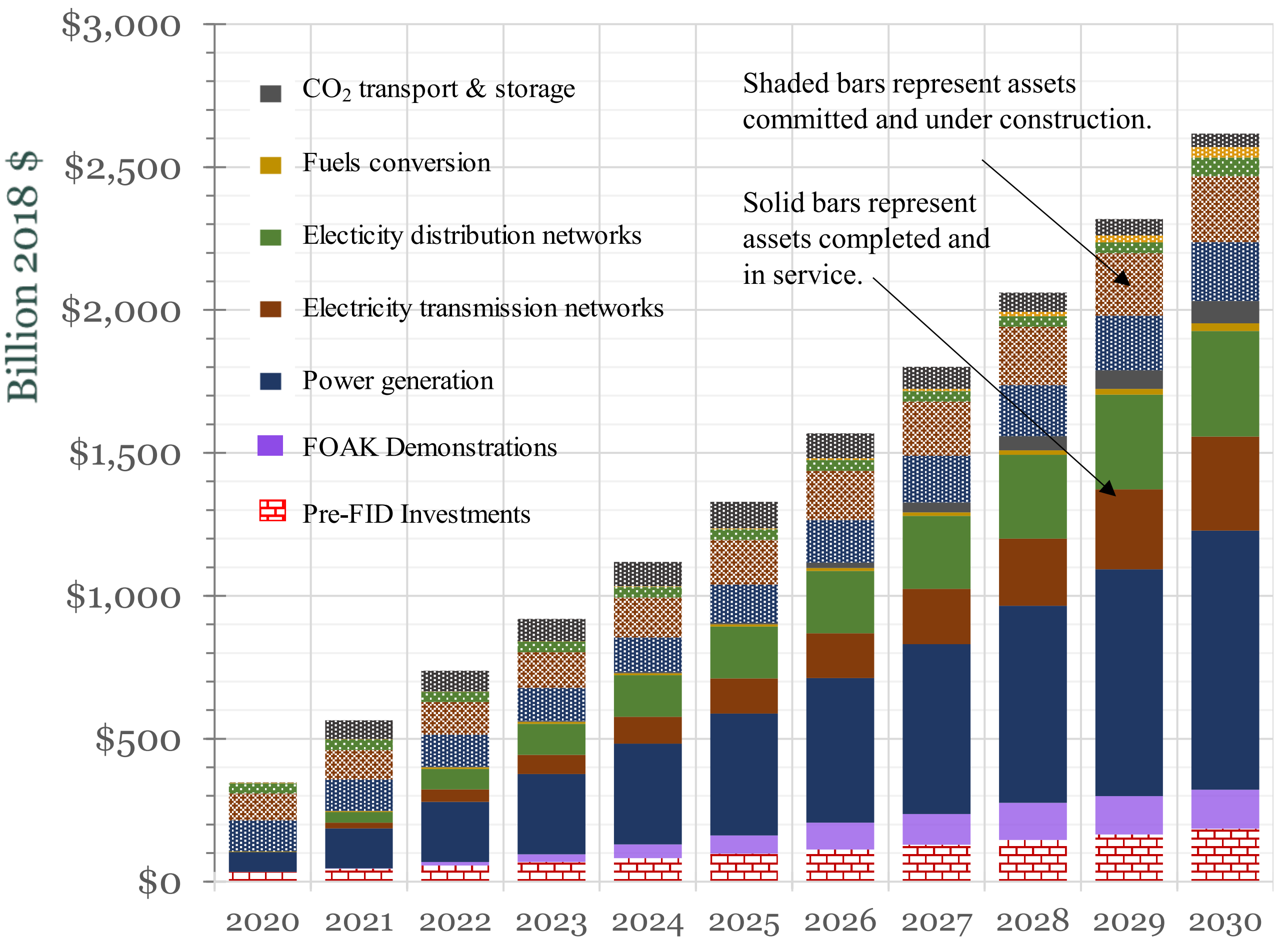


*Figure 7 Chart illustrating the mobilization of $2.6 trillion in supply-side investment capital from during the first decade by sector (including Pre-FID at-risk capital). Solid bars indicate capital projects built and in service, while shaded parts of the bars indicate capital that has been committed and is still under construction.*

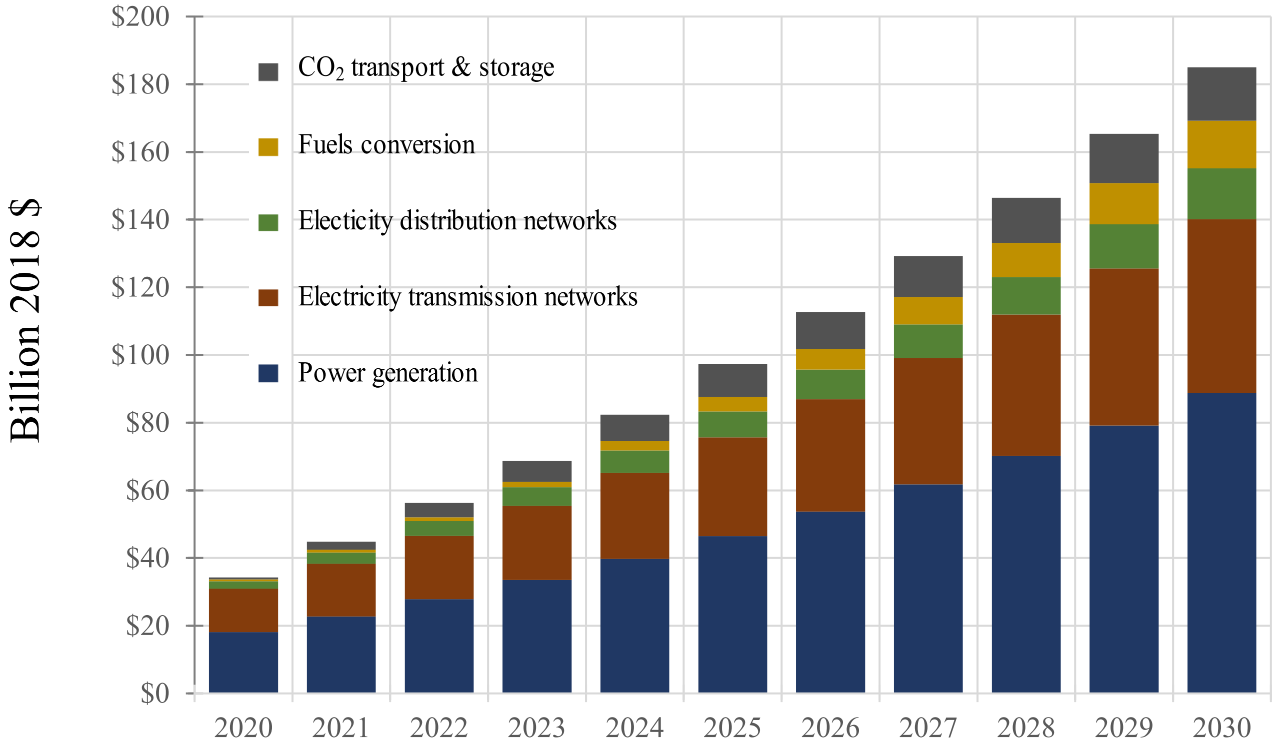


*Figure 8 Chart illustrating the circa $190 Billion of at-risk pre-FID investment required to enable investment capital mobilization depicted Figure 7*

# 7 Incremental Capital Investment (over and above Reference Case)

We also estimate the order of the *incremental* capital for the E+ scenario over and above the Reference Scenario for both supply-side and demand-side investments, during the critical first decade of the transition.

To delineate the supply-side capital investment required in the Reference case, we follow the same procedure described for the E+ scenario in the prior sections of this Annex and supporting Annexes except without the geospatial granularity (e.g. only national sums are estimated). We also analyzed the more significant demand-side investments (especially transport and buildings as described in Annex C) for the purposes of examining the total incremental capital associated with net-zero transitions relative to the reference case. It is worth noting though, that we have not estimated other potentially significant investments associated with establishment of bioenergy crops and decarbonization measures in other industries besides steel and cement (beyond process efficiency improvements).

Figure 9 provides a snapshot of the estimated incremental capital that would be required to be committed in the E+ scenario by 2030, over and above the business-as-usual level of investment for the Reference scenario. The total incremental capital investment is in the order of $2.5 billion (including Pre-FID and FOAK (Option Creation) investments.

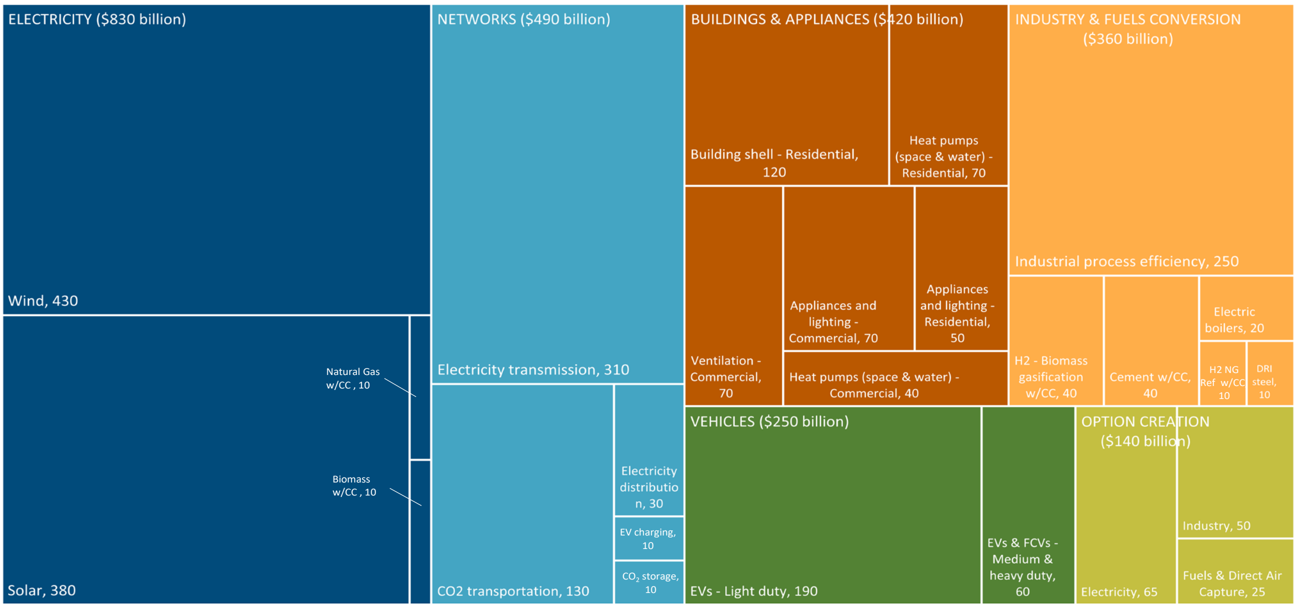


*Figure 9 Snapshot of total incremental capital to be mobilized in the first decade, relative to business as usual without new policies (the Reference Case). Includes capital invested pre-financial investment decision (pre-FID) and capital committed to projects under construction in 2030 but in-service in later years for energy supply plant and infrastructure, and the main demand-side investments in buildings, transport and the cement and steel industries. All values rounded to nearest $10b and should be considered order of magnitude estimates. Figures exclude potentially significant investments associated with establishment of bioenergy crops and decarbonization measures in other industries besides steel and cement.*

# 8 References

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