Potential for US Competitiveness in Emerging Clean Technologies

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1 Executive summary

Challenge and opportunity: The climate crisis presents one of the century's greatest challenges as nations around the world race to limit global warming to 1.5 ºC and avert the worst impacts of climate change. However, in challenge lies opportunity – achieving a global net-zero emissions economy is estimated to require investment of ~$100 to 150 trillion by 2050.[1] Beyond investment, new breakthroughs and business innovations in crucial areas such as zero-carbon firm power, transportation, heavy industry, and carbon removal will be pivotal in the effort to mitigate the climate crisis.

As a global energy and technology leader the U.S. has an opportunity to position itself as a dominant player in the emerging technologies needed to enable the transition to a net-zero economy. Building an early lead in the technologies of the future will create domestic jobs, drive exports, and expand U.S. geostrategic interests in critical areas. Further, building a leading position in emerging clean technologies will offset the economic and societal impacts as the position of high-carbon industries, such as fossil fuels, changes in a net-zero economy.

An impact-oriented approach: This study has prioritized six emerging clean technologies to build a balanced portfolio that can unlock significant carbon abatement potential, drive important economic activity, and enable decarbonization in a range of critical areas. These technologies include:

- **Electric Vehicles (EVs)**
- **Clean steel**
- **Low-carbon hydrogen (H2)**
- **Electrochemical Long Duration Energy Storage (LDES)**
- **Direct Air Capture (DAC)**
- **Advanced nuclear Small Modular Reactors (SMRs)**

The six technologies above were selected from a broader list with the overarching goal of focusing on technologies that could both play a significant role in the energy transition and hold potential for the U.S. to build or maintain durable competitive advantage. While we focused on these six technologies, we recognize the crucial role of more established clean technologies such as wind and solar, as well as broader clusters of technologies such as energy efficiency and electrification.

To focus the analysis on the most impactful segments of each technology's value chain, from raw materials to final sales and support, we assessed each using a three-phase approach:

1. Prioritize value chain segments with large market potential and pathways to build competitive advantage
2. Estimate current and future market value across three IEA scenarios (Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and Net-Zero Emissions Scenario (NZE)) and priority markets; quantify potential societal effects from job growth and impact on communities that have either been historically disadvantaged or will be impacted by the energy transition; and assess current state of relative U.S. competitiveness
3. Identify key enablers to build or maintain competitive advantage in high-value segments

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[1] Climate Finance Markets and the Real Economy: Sizing the Global Need and Defining the Market Structure to Mobilize Capital

Size of the opportunity: The unprecedented levels of investment needed to achieve net zero emissions present an opportunity for the U.S. to build on its history of innovation and become a leader in emerging decarbonization technologies. The six technologies above are estimated to have a cumulative domestic market of $9 to 10 trillion through 2050. Preliminary estimates of potential U.S. exports across these technologies in 2050 indicates ~$330 billion in annual export value, more than the ~$200 billion of U.S. fossil-fuel related exports in 2021.[2] Beyond the economic value provided, collectively the technologies analyzed here could enable approximately 20 Gt/yr in global emissions abatement if adopted at scale by 2050 as the world moves towards a net zero economy. All market values and abatement potential listed below are cumulative numbers from 2022 to 2050 under the APS scenario unless otherwise noted.

- **EVs:** As one of the most mature technologies assessed, EV's present the largest U.S. global SAM, $25 – 30 T in cumulative EV sales
    - The U.S. domestic market is also estimated to be considerable, with total domestic market of $7 – 8 T in EV sales through 2050
    - EVs are also well-positioned to contribute towards net-zero, unlocking 5 – 7 Gt/yr of abatement potential by 2050

- **Clean Steel:** The global clean steel market is estimated to be 20,000 – 25,000 Mt (million tons) cumulatively through 2050, reflecting a market of $10 – 15 T from global steel sales
    - Of this, the U.S. domestic market is expected to require 600 - 700 million tons, representing a market value of $400-480M
    - Global deployment of clean steel to reduce emissions from steel products is estimated to unlock ~1Gt in abatement potential by 2050

- **H2:** Cumulative global low-carbon H2 demand is estimated to be ~1 – 2B metric tons, reflecting a total U.S. SAM value of ~$3 – 4 T for hydrogen produced
    - The U.S. is expected to consume 200 – 250 M metric tons through 2050, reflecting a domestic market of $300 – 400 B
    - Low-carbon H2 is estimated to unlock up to 3 – 5 Gt/yr in annual abatement potential in 2050 in support of a net-zero emissions economy

- **LDES:** Global LDES deployed at scale has a potential cumulative U.S. SAM of $3 – 4 T through 2050
    - U.S. domestic deployment potential is estimated to be 300 – 350 GW through 2050, driving a domestic market opportunity of $1.0 – 1.2 T
    - LDES is considered a critical enabler since it supports the integration of renewable resources into a net-zero energy system. For this reason, the abatement potential was not quantified

- **DAC:** Cumulative global DAC demand is estimated to be ~3 Gt, reflecting a cumulative global market value of $3 – 4T
    - The U.S. market for DAC projects is expected to be substantial, with ~1.9 Gt/yr capacity reached by 2050 and a domestic market through 2050 of ~$1T, calculated as value of sales of carbon credits and CO2 for utilization
    - Under aggressive global targets for decarbonization DAC is estimated to enable negative emissions of up to 5 - 7 Gt/yr by 2050

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[2] Monthly US International Trade in Goods and Services, December 2021

- **Advanced Nuclear SMRs:** Approximately 180 - 220 GW of advanced nuclear SMRs are expected to be deployed globally through 2050, representing $550 – 700 B in CapEx deployed through 2050
    - The U.S. is expected to be one of the largest drivers of this expansion, representing 45 – 55 GW or $140 – 180B investment opportunity through 2050
    - The global deployment of advanced nuclear SMRs may unlock up to ~0.5 Gt/yr in abatement potential by 2050 to enable a net-zero energy system

The U.S.'s potential for durable competitive advantage: The U.S. has the opportunity to build competitive advantage in specific value chain segments across the six technologies evaluated. In general, a dynamic private sector and strong R&D lend the U.S. a competitive edge, though players in Asia and the E.U. often lead the U.S. in the volume of IP or research.

- **EVs:** The U.S., fueled by a strong startup and research base, leads in software and after-sales services and battery chemistry that it can leverage to be a critical supplier for global EVs
    - The U.S. is notably behind in investing to scale innovations across raw materials and manufacturing segments, where Asian players invest heavily

- **Clean Steel:** The U.S. is positioned to grow clean steel manufacturing domestically by leveraging capabilities within existing steelmakers and a leading CCUS industry
    - However, a lack of dedicated U.S.-based OEMs and IP leadership in Europe and Asia suggest the U.S. is not competitive in the export of clean steel-related equipment
    - Additionally, without any carbon tax policies, the U.S. holds a limited position in the offtake of clean steel products, which will suppress growth across all other segments

- **H_2:** Strong domestic policies, infrastructure, an established O&G industry, and abundant natural resources position the U.S. to remain competitive in low-carbon H_2
    - The U.S. is a leader in blue H_2 and has some advantage in green H_2, but faces strong competition from well-established EU players and from low-cost Chinese electrolysers

- **LDES:** U.S.-based companies have built an early lead in the electrochemical LDES space, although they lag Chinese, South Korean, and Japanese players in research and IP
    - Long-term advantage will depend on which players can quickly reduce costs by mastering the advanced manufacturing processes needed to efficiently build battery modules at scale

- **DAC:** The U.S. is well positioned to lead DAC development at scale due to abundant geological storage formations and potential in affordable renewables and low-carbon energy
    - Synergistic O&G industry technology can help the U.S. maintain this advantage while U.S.-based next-generation OEMs build greater expertise and advantage through new IP and innovation
    - However, the lack of DAC offset quality standards and a federal marketplace limits the DAC market, potentially slowing progress of U.S. players relative to others like the E.U.

- **SMRs:** The U.S. is well positioned to lead in the advanced nuclear SMR space, with significant private investment and early leadership in IP and research
    - Though the U.S. does not currently have a clear advantage in strategically important uranium enrichment, significant disruptions in the highly concentrated space led by Russia creates a valuable opening for the U.S. to build a strong position

Enablers of advantage: Several key enablers of competitive advantage were identified across all six technologies. Enablers include both push from the supply side and pull from increased demand, to aid U.S. companies in building durable competitive advantage across technologies.

Demand pull: Enhance competitiveness by creating a more favorable environment for domestic players to grow. Examples include:

- **Decrease green premiums:** Increase demand by either reducing the cost of the technology or increasing the cost of emitting alternatives
- **Increase volumes deployed:** Increase total technology deployment through direct procurements or deployment targets
- **Ensure access to export markets:** Increase demand for domestic companies' exports by clearing non-tariff barriers

Supply push: Boost competitiveness by building economies of scale through investment in manufacturing and maintain lead in product quality through R&D. Examples include:

- **Streamline deployment:** Reduce barriers to deployment to de-risk investment in projects, increasing number of projects deployed and driving costs down the learning curve
- **De-risk project and infrastructure investment:** Increase access to capital for relevant projects / infrastructure, decreasing technology costs
- **Maintain lead in quality / cost through innovation:** Promote R&D to maintain technological competitiveness in product quality and /or cost

Specific recommendations are given for each technology at both the overall technology level as well as at the individual value chain segment level.

Next steps: This analysis focused on the highest priority areas with potential for the U.S. to build durable competitive advantage and identified the methods to do so. The next step to translate this analysis into action is to formulate specific policy and investment proposals and work with relevant stakeholders to build support for implementation. Through well-crafted policy and stakeholder support, the U.S. could become a dominant player in the emerging technologies needed to avert the worst impacts of climate change.

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3 Introduction

An estimated $100-150T investment is needed through 2050 to transition to a low-carbon economy[2], demonstrating the aggressive growth of the global clean technology market. Investment of this magnitude creates an opportunity for the U.S. to build on a history of innovation and become a leader across emerging technologies for decarbonization. To achieve leadership and true differentiation, the U.S. must strategically invest in innovation and scale technologies needed to reach net zero emissions goals. The U.S. should target investment and growth in the value chain segments of these technologies that offer the largest opportunity to build and protect a competitive edge.

This collective action poses an incredible opportunity for the U.S., especially given the country's history of innovation and investment in scaling clean technology. To realize the potential value from clean technology deployment and sustain this competitive position into the future, the U.S. must strategically invest and innovate in these rapidly growing technologies. By focusing on clean technology value chain segments with the highest potential and capitalizing on existing strengths to build or maintain durable competitive advantage, the U.S. can capture its fair share of this market while advancing global climate goals.

Doing so will also generate long-term societal benefits for the U.S. A strong U.S. positioning in clean technologies is relevant for environmental justice and will provide jobs to create a resilient workforce that can benefit parts of the country most affected by the energy transition or communities that have been historically disadvantaged. Transitioning to clean technologies can decrease negative environmental impacts of current technologies, while boosting the economy of surrounding communities.

There are also the geostrategic and national security aspects: Many of these technologies have direct defense applications and increased domestic energy output (e.g., of SMR, low-carbon H_2) will enhance energy security. Further, growing clean technologies can help offset the roughly $200B annual fossil fuel exports from the U.S. as the global energy sector transitions[2].

To select technologies, we looked at technologies with the highest potential impact in terms of carbon abatement and economic benefit, and those that are immature enough for policy and investment decisions made now to have a significant impact on their trajectory. The six technologies selected for further analysis were:

- **Electric Vehicles** (**EVs**)
- **Clean steel**
- **Low-carbon hydrogen** (**H_2**)
- **Electrochemical Long Duration Energy Storage** (**LDES**)
- **Direct Air Capture** (**DAC**)
- **Advanced Nuclear Small Modular Reactors** (**SMRs**)

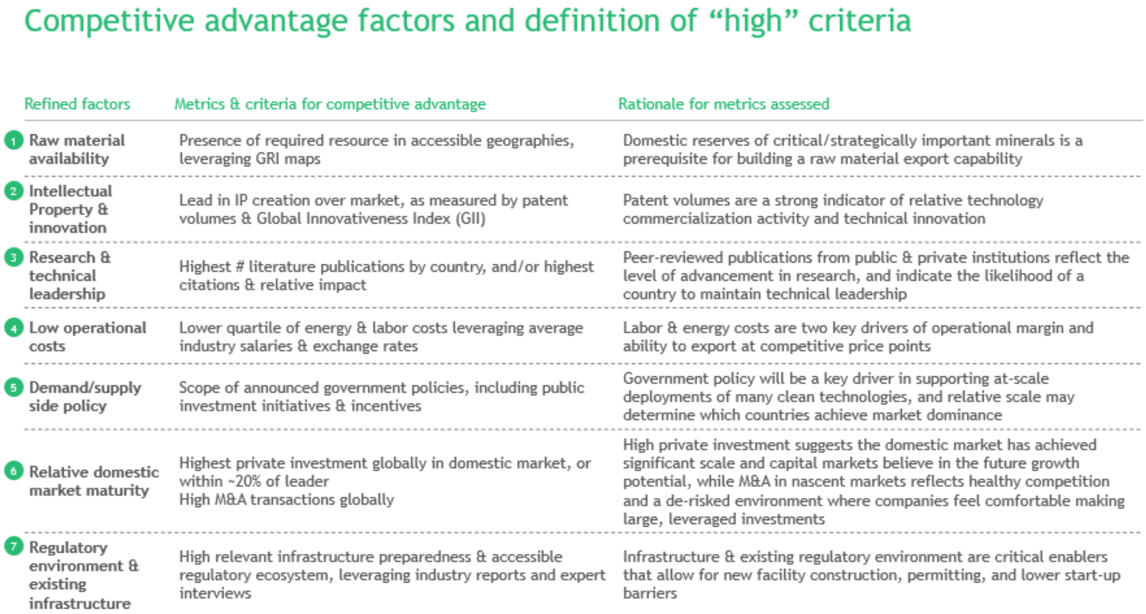
For each of the six technologies, market size, ability to build competitive advantage, and job creation potential were analyzed across the value chain to determine prioritized segments for building or maintaining competitive advantage. Market potential was estimated using three different IEA scenarios that represent different commitment to emissions reduction (net-zero, announced pledges, and stated policies). For each value chain segment, market sizes were calculated for the U.S., key export markets, and the total global market.

Current U.S. competitiveness was assessed using seven dimensions that include factors like intellectual property, existing infrastructure, and low operational costs (see Figure 3.1). The U.S.

was compared to other major global players using data points like patent activity and private investments for each technology. Through this analysis and interviews with 80+ experts, we identified key challenges to the U.S. building and maintaining competitive advantage. Finally, we crafted recommendations to address these challenges and enable the U.S. to capture its fair share of these emerging climate technologies. See section 9 for further details on our methodology.

3.1 Context for proposed recommendations

Throughout our analyses, we focused on what actions could build or maintain durable U.S. competitive advantage, especially for prioritized segments. Interviews with more than 70 experts (see Section 12 – Acknowledgements for Partner Organizations) informed our summary of key challenges for adoption and recommendations for strategic investments and policies the U.S. could put in place to aid in transition to these clean technologies. Recommendations presented in this study are not exhaustive and should be considered as a set of example actions to address key challenges to building or maintaining U.S. competitive advantage. We encourage and welcome additional recommendations for policy and investment actions to build upon the information in this report. We discuss our key findings in detail in the following technology deep-dive sections.



Competitive advantage factors and definition of “high” criteria

Refined factors	Metrics & criteria for competitive advantage	Rationale for metrics assessed
① **Raw material availability**	Presence of required resource in accessible geographies, leveraging GRI maps	Domestic reserves of critical/strategically important minerals is a prerequisite for building a raw material export capability
② **Intellectual Property & innovation**	Lead in IP creation over market, as measured by patent volumes & Global Innovativeness Index (GII)	Patent volumes are a strong indicator of relative technology commercialization activity and technical innovation
③ **Research & technical leadership**	Highest # literature publications by country, and/or highest citations & relative impact	Peer-reviewed publications from public & private institutions reflect the level of advancement in research, and indicate the likelihood of a country to maintain technical leadership
④ **Low operational costs**	Lower quartile of energy & labor costs leveraging average industry salaries & exchange rates	Labor & energy costs are two key drivers of operational margin and ability to export at competitive price points
⑤ **Demand/supply side policy**	Scope of announced government policies, including public investment initiatives & incentives	Government policy will be a key driver in supporting at-scale deployments of many clean technologies, and relative scale may determine which countries achieve market dominance
⑥ **Relative domestic market maturity**	Highest private investment globally in domestic market, or within ~20% of leader High M&A transactions globally	High private investment suggests the domestic market has achieved significant scale and capital markets believe in the future growth potential, while M&A in nascent markets reflects healthy competition and a de-risked environment where companies feel comfortable making large, leveraged investments
⑦ **Regulatory environment & existing infrastructure**	High relevant infrastructure preparedness & accessible regulatory ecosystem, leveraging industry reports and expert interviews	Infrastructure & existing regulatory environment are critical enablers that allow for new facility construction, permitting, and lower start-up barriers

Figure 3.1 – 7 Dimensions of competitive advantage to assess U.S. competitiveness

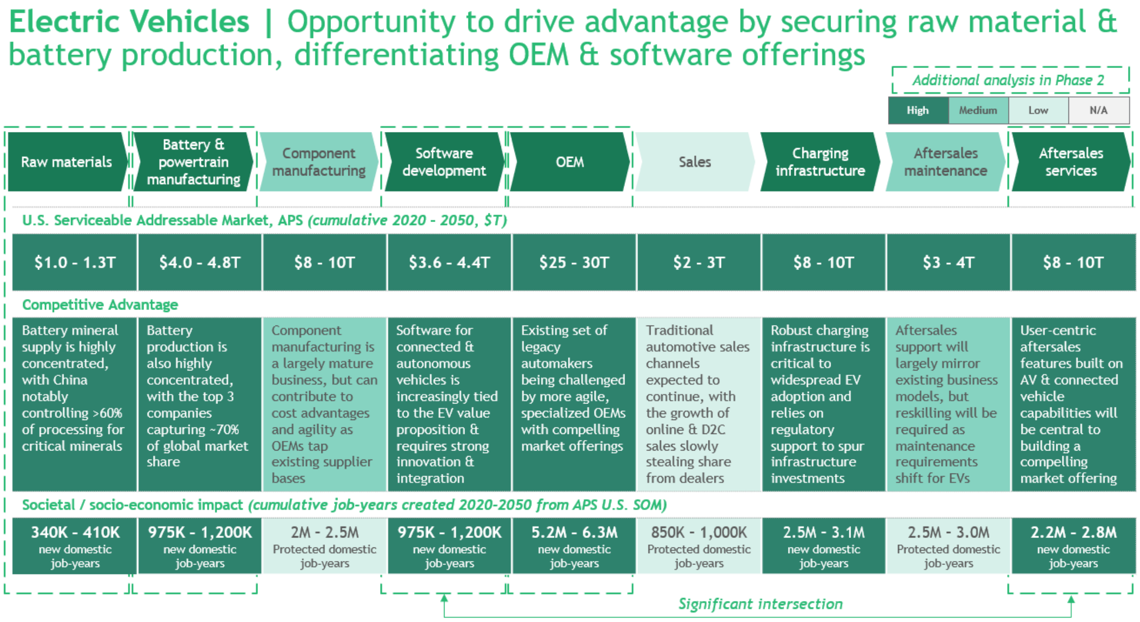
4 Electric Vehicles

Electric vehicles (EVs) consist of consumer and commercial plug-in battery-electric vehicles. They are functionally similar to a traditional internal combustion engine (ICE) vehicle, with the powertrain replaced by an induction electric motor paired with a lithium-ion battery pack and corresponding electronic control systems. This study focuses primarily on the passenger cars with some evaluation of light/medium-duty transportation sectors. It excludes heavy-duty transportation and vehicles with hybrid-electric powertrains.

Electric vehicles are expected to be the fastest-growing segment of the automotive sector, fueled by increasing consumer adoption, a robust startup ecosystem, and strong commitments from legacy automakers to transition to EV powertrains. Passenger cars were the fourth-largest export category for the U.S. in 2021, according to the Census Bureau's Foreign Trade Data[3], and EVs are expected to become an increasingly key piece of maintaining and growing these exports as the world electrifies.

4.1 Overview of value chain segments considered for this study

The EV value chain is distinct from many others in this study because it is a non-commodity (vs. electricity, steel, or hydrogen, for example), a consumer product, and an evolution of an existing industry versus an entirely new market. A detailed view of the full EV value chain analyzed is included on appendix page 67.



Electric Vehicles | Opportunity to drive advantage by securing raw material & battery production, differentiating OEM & software offerings

	Raw materials	Battery & powertrain manufacturing	Component manufacturing	Software development	OEM	Sales	Charging infrastructure	Aftersales maintenance	Aftersales services
U.S. Serviceable Addressable Market, APS *(cumulative 2020 - 2050, $T)*	$1.0 - 1.3T	$4.0 - 4.8T	$8 - 10T	$3.6 - 4.4T	$25 - 30T	$2 - 3T	$8 - 10T	$3 - 4T	$8 - 10T
Competitive Advantage	Battery mineral supply is highly concentrated, with China notably controlling >60% of processing for critical minerals	Battery production is also highly concentrated, with the top 3 companies capturing ~70% of global market share	Component manufacturing is a largely mature business, but can contribute to cost advantages and agility as OEMs tap existing supplier bases	Software for connected & autonomous vehicles is increasingly tied to the EV value proposition & requires strong innovation & integration	Existing set of legacy automakers being challenged by more agile, specialized OEMs with compelling market offerings	Traditional automotive sales channels expected to continue, with the growth of online & D2C sales slowly stealing share from dealers	Robust charging infrastructure is critical to widespread EV adoption and relies on regulatory support to spur infrastructure investments	Aftersales support will largely mirror existing business models, but reskilling will be required as maintenance requirements shift for EVs	User-centric aftersales features built on AV & connected vehicle capabilities will be central to building a compelling market offering
Societal / socio-economic impact *(cumulative job-years created 2020-2050 from APS U.S. SOM)*	340K - 410K new domestic job-years	975K - 1,200K new domestic job-years	2M - 2.5M Protected domestic job-years	975K - 1,200K new domestic job-years	5.2M - 6.3M new domestic job-years	850K - 1,000K Protected domestic job-years	2.5M - 3.1M new domestic job-years	2.5M - 3.0M Protected domestic job-years	2.2M - 2.8M new domestic job-years

Figure 4.1 - Electric Vehicle Value Chain Prioritization Results

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[3] Monthly US International Trade in Goods and Services, December 2021

In assessing areas for deep-dive analyses, the study focused on four key areas:

1. **Raw materials:** Vehicle electrification will drive a massive demand increase for battery minerals, with the IEA projecting 10-fold growth in battery-driven mineral demand by 2040 in the "business as usual" STEPS scenario, and a 40-fold increase in the Sustainable Development Scenario. This demand will be concentrated in the growing need for lithium, nickel, graphite, cobalt, and copper, and will be a key part of overall EV supply chain security.

2. **Battery and powertrain manufacturing:** Vehicle performance and price are predominantly defined by this segment, and successfully deploying differentiated vehicles will depend on both battery manufacturing itself and the upstream production of materials including electrodes, electrolytes, and separators.

3. **OEM:** By far the largest segment in terms of revenue, representing ~60% of overall value across modeled segments, the success of new and legacy OEMs will be critical to capturing value in EVs, as the manufacturer plays a key role in designing, integrating, and producing a compelling market offering.

4. **Software development and after-sales services:** The development and deployment of advanced car features, including Advanced Driver Assistance Systems (ADAS), autonomous vehicle, and connected car offerings, are increasingly integrated with EVs and key to product differentiation.

4.2 Size of the opportunity in domestic market and exports

The domestic market is expected to be the largest opportunity for U.S.-based EV manufacturers in the near term, followed by Canada, Europe, and China. The U.S. Serviceable Addressable Market (SAM) for electric vehicles is expected to be ~$27T in cumulative value through 2050 in the APS scenario, rising from ~$150B annually today to ~$1.4T in 2050. The broader range for this projection is ~$14T in the STEPS scenario, and ~$44T in the NZE. Unlike many other technologies discussed in this report, the strong existing momentum in the private sector behind the transition to electric vehicles is expected to push the likely market scenario closer to the NZE, corresponding to a $4.3T market across modeled segments in 2050.

A large portion of this value will flow upstream to critical suppliers, with ~$2T and $8T expected in the battery and powertrain manufacturing and raw materials segments, respectively, in the NZE through 2050. Software development and after-sales services, largely dominated by subsegments that center around autonomous driving (including ride-hailing services), total $4-6T (APS) and $9-15T (NZE) cumulatively through 2050. China is also projected to be a major near-term export opportunity, but growth in 2028 and beyond is expected to plateau as market share is largely captured by domestic Chinese players. Important foreign countries and regions broken out in this analysis are detailed in Table 1, below.

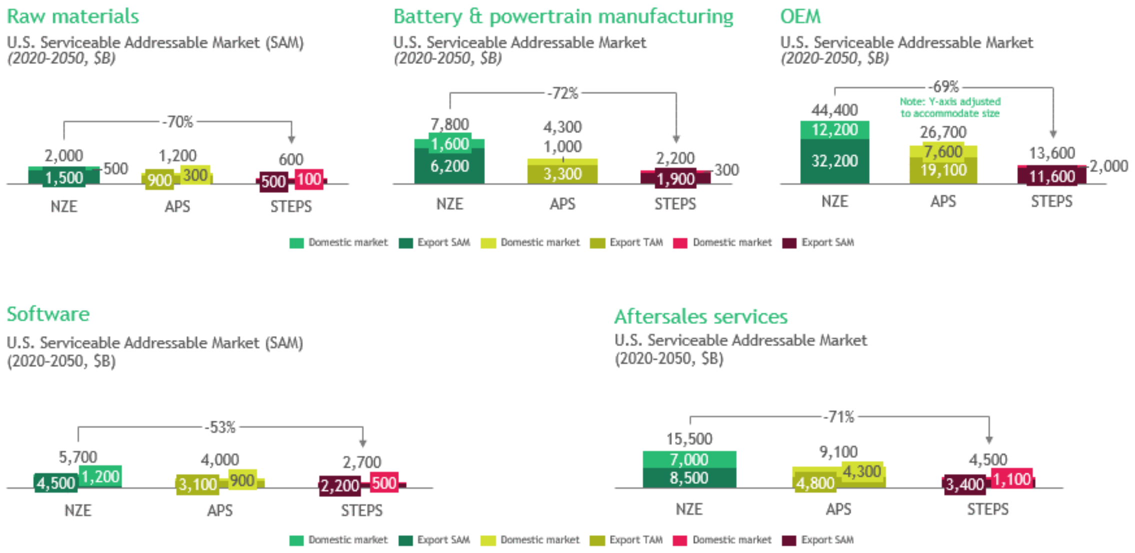


Figure 4.2 - Cumulative Deployment Potential by Priority Market

The U.S. Serviceable Obtainable Market (SOM), which reflects the portion of the global market which U.S.-based companies could realistically capture, is estimated to be 10 – 55% of the global market based on precedents set by the EV, legacy passenger vehicle, and SaaS industries. The lower bound of the range is based on the current estimated U.S. share of global EV production while the upper bound is based on the global leader in passenger vehicle production (China) for raw materials, battery and power train manufacturing, OEM. The upper bound for remaining segments (software, aftersales services) is based on the global leader in SaaS markets, which is the U.S. This range reflects the spread of market share which the U.S. could potentially capture, with the lower bound (~10%) reflecting business as usual without strategic support while the upper bound (~55%) reflects what a market leader could capture. U.S.-based players, particularly in the OEM and battery and powertrain manufacturing segments, can achieve market share closer to the upper bound by building a competitive moat through early leadership in innovative technologies, by capturing economies of scale in manufacturing, and developing expertise and IP in relevant advanced manufacturing processes.

Priority Markets	**Segments included in SAM**	Relevant Drivers for Market Deep Dive
European Union	• Raw materials • Battery and powertrain manufacturing • OEM • Software and after-sales services	• The EU is seeing increased EV investment and has strong regional automakers with plans to grow local battery manufacturing • Collectively, the EU is the second-largest importer of U.S.-made vehicles • Local automakers are also likely to leverage U.S.-built software platforms over Chinese offerings due to security concerns
Japan	• Raw materials • Battery and powertrain manufacturing • OEM	• Japan is a major automaking nation and is a potential market for key inputs, particularly software platforms as OEMs integrate advanced features into offerings

Priority Markets	**Segments included in SAM**	Relevant Drivers for Market Deep Dive
	• Software & after-sales services (focus area)	• Major domestic BEV production will limit ability for Western suppliers to break into market
Canada	• Raw materials • Battery and powertrain manufacturing • OEM (focus area) • Software & after-sales services	• Canada is the largest U.S. car export market and will continue to be a major target as U.S. EV OEM direct sales grow
China	• Raw materials • Battery and powertrain manufacturing • OEM • Software and after-sales services	• China is the dominant battery hub today and will continue to be a minerals and components market in the immediate future. However, as China works to build greater control over upstream mineral mining, initiatives suggest the country will insource the majority of new supply sources in the mid/long-term • China is the largest car market globally and a major U.S. automotive importer. It is expected to continue purchasing U.S. EVs and integrated services, but as the domestic market matures, share may be limited as the environment favors domestic OEMs • Public and private momentum is pushing for greater domestic control of the supply chain, likely limiting the addressable market share across value chain segments in 2028 and beyond

Table 3.1- Detail on independently modeled countries and regions

4.3 Segment level analysis

4.3.1 Raw materials

- Nearly 50% of the global market through 2030 resides in China in the STEPS scenario due to existing investment and policies, versus ~30% in the NZE as Western nations increase investment
- As new growth in the Chinese market is captured by domestic players in 2028 and beyond, addressable share drops to ~25-35% of the global market
- China comprises ~30-50% of global battery mineral margin pool over the next decade as EV production and demand rapidly expands
- While margins are traditionally low in metals mining, observed and expected volatility in commodity prices can drive significant variation and are a major sensitivity in these projections
- As a result, supply/demand mismatches may drive market size and margin potential upside

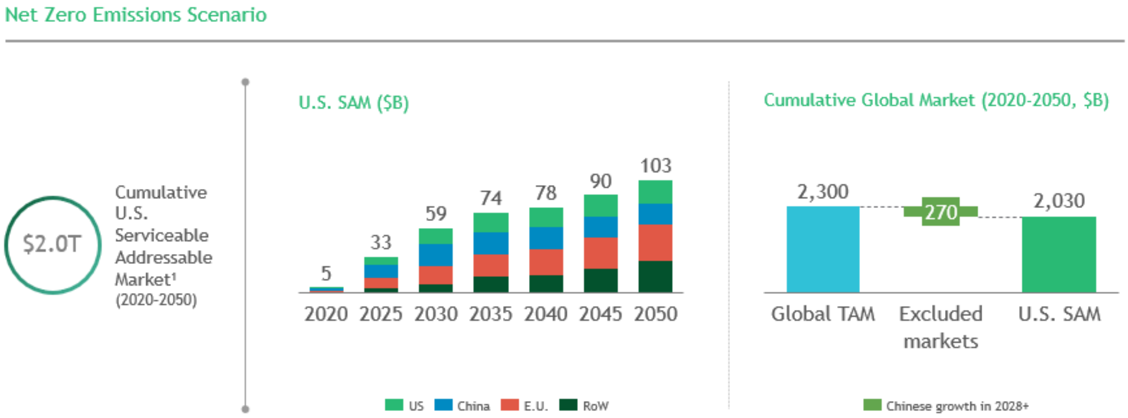


Figure 4.3 - Raw materials annual market value, Net Zero Emission Scenario (NZE)

4.3.2 Battery and powertrain manufacturing

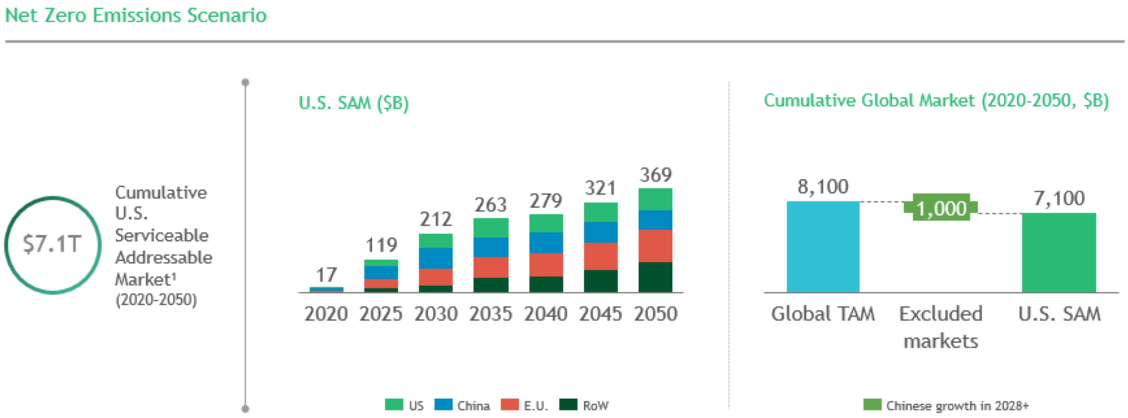


Figure 4.4 - Battery and powertrain manufacturing annual market value, Net Zero Emission Scenario (NZE)

- Following a similar trend as raw materials, ~40-50% of the global market through 2030 resides in China in the STEPS scenario due to existing investment and policies, versus ~35% in the NZE scenario as Western nations increase investments
- Due to onshoring momentum in China, inputs and manufacturing in the Chinese market are expected to be primarily captured by domestic players in 2028 and beyond, limiting the addressable share to 20% of the global market in the NZE
- Margin pool is expected to increase ~3x between STEPS and NZE as North American and European markets expand significantly. Margin pools are the expected gross profit for a total market, calculated by multiplying gross profit margin by total market size.
- Overall margins are expected to remain modest, in the ~6% range, as many players compete on price

4.3.3 OEM

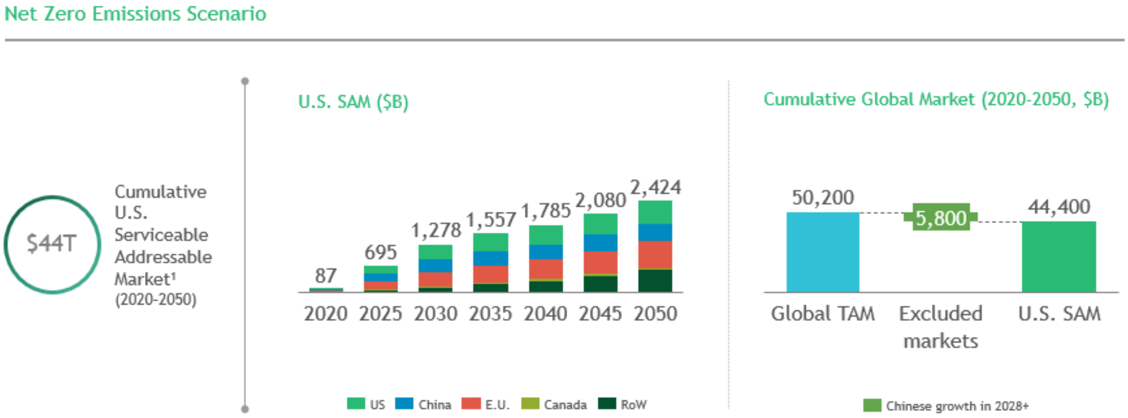


Figure 4.5 - OEM annual market value, Net Zero Emission Scenario (NZE)

- As the largest single market segment, OEM production is a major opportunity across scenarios with a projected lower bound of ~$14T in cumulative market value through 2050 in the current trajectory STEPS case
- The domestic market remains comparatively small in the STEPS scenario, at just 15% of the global market, as other regions implement more aggressive policies. However, with aggressive action, the U.S. SAM is ~30% of TAM in the NZE and 6x the cumulative value in STEPS

4.3.4 Software development

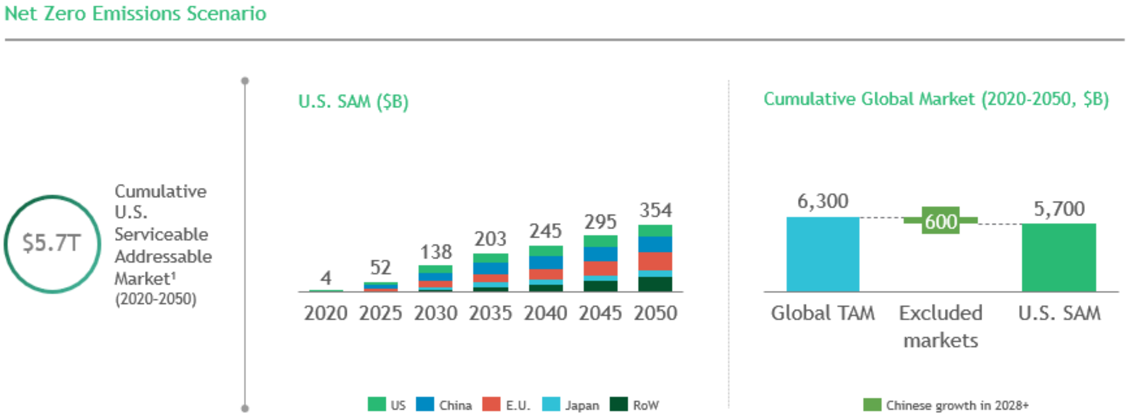


Figure 4.6 - Software development annual market value, Net-Zero Emission Scenario (NZE)

- The overall software development market takes time to mature as applications reach viability, with most commercial deployments not realized until 2028 and beyond, and over 90% of cumulative market value taking place in 2030-2050
- Chinese OEMs are highly unlikely to select U.S.-built platforms in domestic-made vehicles, but some market opportunity still exists in the near term through integration into U.S. vehicle exports

4.3.5 After-sales services

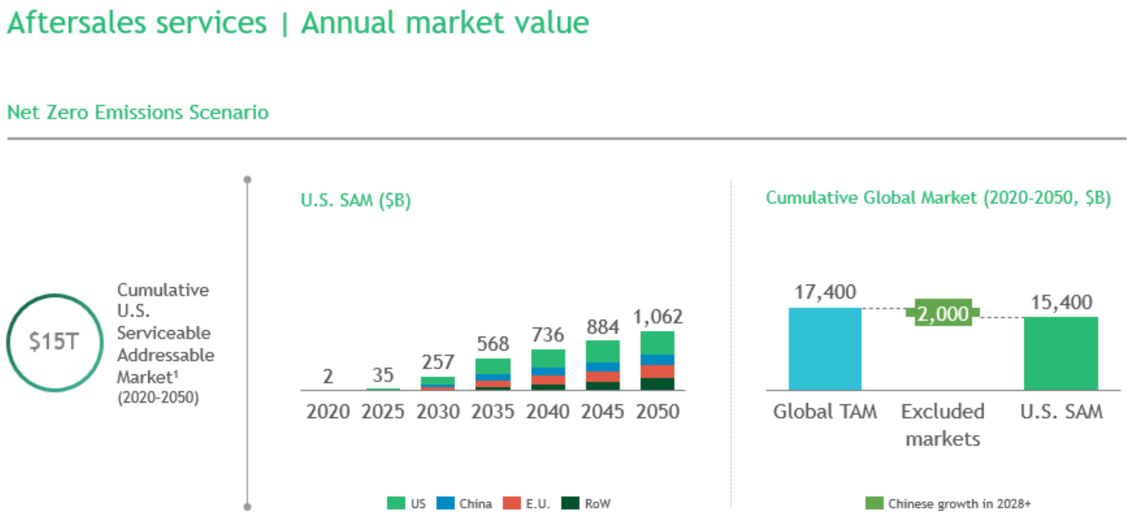
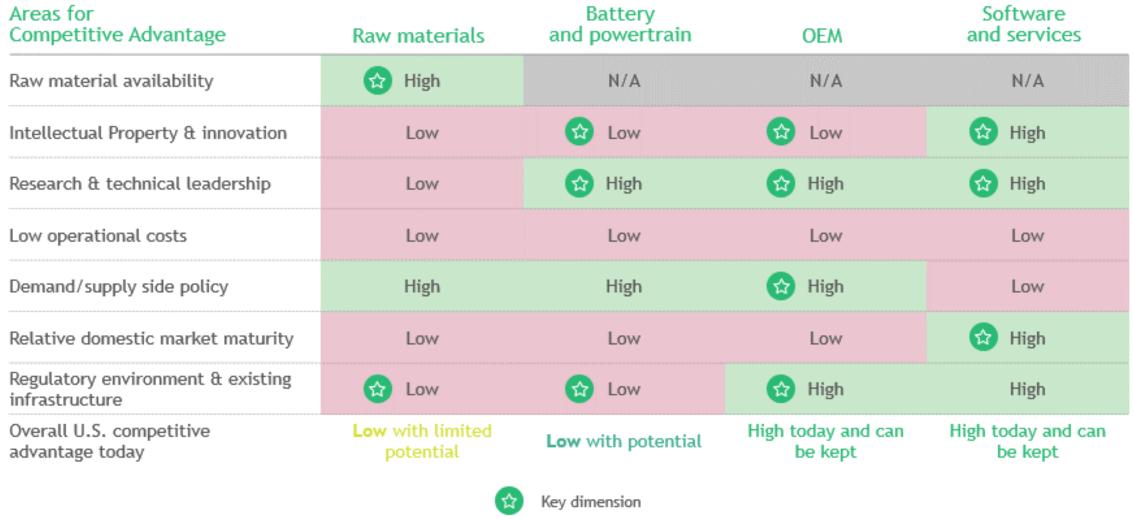


Figure 4.7 - After-sales services annual market value, Net Zero Emission Scenario (NZE)

- As with upstream software development, much of the after-sales services market relies on the development of advanced features such as autonomous and connected vehicles, which do not reach widespread commercial viability until 2028 and beyond. As a result, nearly 100% of cumulative market value is in 2030-2050
- The segment experiences rapid growth in 2035-2050 as autonomous vehicles reach cost advantage over traditional taxis and ride-hailing
- The U.S. is expected to be the largest single market, representing over 40% of the global market in the NZE
- Near-term losses are expected to be offset as most providers reach net profitability in 2033 and beyond

4.4 Overview of competitiveness

Figure 4.8 below summarizes U.S. competitive advantage across the four prioritized segments, OEM and O&M software. Current U.S. competitive advantage is classified as "High" or "Low" (see Figures 3.1 and 10.3 for methodology), with a summary ranking in the final row that is used for plotting in Figure 10.12. Recommendations focus on key dimensions, denoted by the green star, because these dimensions must be unlocked to create durable competitive advantage. Explanations of competitive advantage ranking and key dimensions by value chain segment are included below.



Areas for Competitive Advantage	Raw materials	Battery and powertrain	OEM	Software and services
Raw material availability	✪ High	N/A	N/A	N/A
Intellectual Property & innovation	Low	✪ Low	✪ Low	✪ High
Research & technical leadership	Low	✪ High	✪ High	✪ High
Low operational costs	Low	Low	Low	Low
Demand/supply side policy	High	High	✪ High	Low
Relative domestic market maturity	Low	Low	Low	✪ High
Regulatory environment & existing infrastructure	✪ Low	✪ Low	✪ High	High
Overall U.S. competitive advantage today	Low with limited potential	Low with potential	High today and can be kept	High today and can be kept

✪ Key dimension

Figure 4.8 - Current U.S. competitive advantage across key areas, by segment

Key Electric Vehicle competitiveness findings include:

- Raw Material Availability (High): Particularly relevant for the raw materials value chain segment, the U.S. has significant lithium brine reserves in southwestern states as well as the necessary extraction technologies. Additionally, the U.S. has small amounts of known cobalt and nickel reserves as well. limited existing extraction operations across all minerals. Canada also hosts reserves that could be leveraged to build the overall North American supply chain

- Intellectual Property & Innovation (Mixed): This dimension was relevant across the battery and powertrain manufacturing, OEM, and aftersales services segments. The rationale for each includes:

    - Battery and powertrain manufacturing (Low): The U.S. is currently outpaced in total relevant patenting volume by a factor of 2 – 3x by China, Japan, and South Korea. South Korea market leaders such as LG Chem and Samsung are investing heavily in research while South Korea more broadly climbs into the top 5 countries on the Global Innovation Index. Further, U.S. patent leaders skew upstream towards battery materials and novel battery chemistry research, while foreign manufacturers that focus more on production innovations which could provide a more direct manufacturing cost advantage

    - OEM (Low): U.S. EV OEM lags in patents volumes, ranking 5th globally after China (+200% vs. U.S.), South Korea (+190%), Japan (+40%), and Germany (+25%) as automakers in those regions invest heavily in EV transition. Toyota and Hyundai the notable leaders in EV OEM patent activity as Asian automakers drive towards automation and manufacturing improvements, but Ford in 3rd place with >700 patents since 2015 as only U.S. automaker in top 15 patent entities globally

    - Aftersales services (High): The U.S. possesses clear lead in vehicle software patents, with 80% more publications since 2015 than the next leading countries

China, South Korea, and Germany. Further, U.S. players enjoy a diverse ecosystem within the U.S. across the connected/autonomous vehicle value chain. Auto OEMs, AV/connected vehicle startups, and critical hardware inputs such as lidar & computing components all drive significant patent activity.

- Research and Technical Leadership (High): This dimension was “High” across battery and powertrain manufacturing, OEM, and aftersales services segments. This is despite the U.S. often lagging China in terms of absolute research publications by as much as ~2x, as in the case of battery-related research, as U.S. research is typically viewed as much higher quality. This is confirmed by the number of citations U.S. research attracts, which is generally viewed as a proxy for paper quality as leading research is often cited in other academic studies. Further, the U.S. continues to outproduce all other countries in terms of research volume and quality, giving it a strong advantage in this area.

- Demand and Supply Side Policy (High): Most relevant for the OEM segment, a varying set of EV purchase incentives from both Federal and State governments (such as the Federal EV Tax Credit) have helped to drive EV adoption. Notably however, the investment size is outpaced by similar policies in China, which allocated ~$6B USD in the 2022 fiscal year budget for NEV purchase subsidies.

- Relative Domestic Market Maturity (High): Focused on the aftersales services market, U.S. AV/connected vehicle investment significantly outpaces the rest of the world, with domestic private investment totaling more than the next 10 countries combined as the clear technical leaders begin to deploy commercial applications of key products.

- Regulatory Environment and Existing Infrastructure (Mixed): This dimension was determined to be “Low” for the raw materials and battery and powertrain manufacturing segments and “High” for the OEM segment. Drivers for each include:

    - *Raw materials (Low):* Non-uniform and often stringent environmental policies can be major inhibitors of new mining/extraction sites. Further, disparate state restrictions combined with a slow permitting policy stimy new initiatives to develop resources domestically, with new mineral mines in the U.S. taking 7-10 years to receive permit approval compared to 2-3 years in countries with similar environmental standards such as Canada and Australia.

    - *Battery and powertrain manufacturing (Low):* Similar to raw materials, permitting policy can limit the pace at which battery input & component manufacturers can construct new facilities, although the impact is relatively limited vs. mining operations.

    - *OEM (High):* Strong legacy infrastructure, policy, and market structures in place to support automakers given strong positions held by U.S. legacy automakers.

4.5 Summary of findings

As an emerging clean technology with one of the largest potential market sizes, the EV space is hotly contested by players across multiple countries. Despite being well-positioned to compete, particularly in the aftersales services software space, maintaining competitive advantage will require a strong presence of U.S. companies across the EV value chain. The prominent position of early U.S. players is challenged by both a variety of supply chain risks as well as accelerating momentum of U.S. competitors in IP, R&D, and investment. Further, a rapid rollout of public and private charging infrastructure will also be required to support the global EV transition. Many regions are unprepared for the surge in electrical demand required, with grids requiring significant upgrades. These key challenges and potential solutions are expanded upon below. If left unaddressed, the challenges limit both a potential domestic market and the export competitiveness for U.S. players. These two concepts are intertwined, as a robust domestic market gives U.S. players the opportunity to integrate secure supply chains and develop cost advantages through automation and economies of scale.

Technology-wide: The U.S. is notably behind peers in both investment and innovation across the upstream raw materials, battery and powertrain, and OEM segments as Asian players invest heavily in research and scaling. The U.S. does possess strong leads in software and after-sales services as well as upstream battery materials IP; it can leverage those to be critical suppliers for the global EV transition. Despite a research base publishing high-quality literature across all segments, this has not clearly translated into patents or commercial growth for the U.S. Primary challenges to address include:

Challenge A: The U.S. is lagging in IP generation to East Asian players in multiple areas except aftersales services software. As discussed in the "Overview of EV Competitiveness" section above, the U.S. lags in patenting activity to China, Japan, and South Korea, often by significant margins. Selection of **potential actions**:

- Regain U.S. lead in basic research: The U.S. must continue to grow its investment in broad-based fundamental and applied research programs to continue building the leading next-generation capabilities. Example levers may include:
- Grow research and demonstration funding directed to critical EV-related areas including AI/ML, automation and robotics, semiconductors and chip design, and battery chemistry

Raw materials: The U.S. has no clear path to overall leadership in battery critical minerals today, due to dominant East Asian control of processing, Chinese investments in the mining space, and geographic concentration of known mineral reserves. China possesses massive leads in both investments and IP innovation across mineral extraction and processing technologies. However, the U.S. has a clear playbook to securing a domestic supply chain for lithium, negotiating access to reserves of other minerals among international partners, and building an independent processing industry to begin reducing supply chain risks. Primary challenges to address include:

Challenge B: U.S. players face significant raw materials supply chain risks. Battery mineral supply is concentrated, with China notably controlling >60% of critical mineral processing capacity. Further, much of the mining of critical is also owned by China, including ~75% DRC Cobalt, ~50% of Australian Lithium, ~30% of Chilean Lithium, and ~50% Indonesian Nickel production.[4] Given the high demand and limited supply of these critical minerals, such a concentration of access may limit the competitiveness of U.S. players in multiple downstream value chain segments. Selection of **potential actions:**

- Secure access to domestic and foreign mineral extraction: Securing access to mineral reserves could be supported through initiatives that coordinate public and private

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[4] Global lithium-ion battery capacity to rise five-fold by 2030; 2022 Eye on the Market Energy Paper; As lithium-ion battery materials evolve, suppliers face new challenges, World Steel in Figures 2022, Lithium Statistics and Information, Commodities Outlook

investments in key mines. Supporting domestic extraction growth by streamlining permitting and providing supply-side support may also accelerate domestic growth. Example levers may include:

  - Launch initiatives with coordinated joint oversight by appropriate agencies (e.g., EXIM, Treasury) to coordinate investments in key foreign mineral operations
  - Increase access to domestic mineral production (e.g., streamline site permitting, open public lands, work with environmental stakeholders from Phase 0, unify mineral recycling regulations)
  - Adjust import tariff structures with nations critical to the global mineral supply (e.g., Australia, Chile, Democratic Republic of the Congo) to promote import of minerals as feedstock for U.S.-based mineral processing capacity
  -

- Ensure access to processed minerals: Support access to mineral processing capacity, either domestic or via trusted trading partners, may help secure the U.S. position in the global EV supply chain by de-risking key raw material bottlenecks. Example levers may include:
  - Provide production subsidies for domestic processing of key minerals including lithium, cobalt, and nickel. Extending similar production incentives to the recycling industry may also help support a circular ecosystem
  - Implement export tariffs for end of life (EOL) batteries with valuable chemistries (e.g., NMC) to reduce U.S. mineral leakage and support recycling ecosystem
  - Launch initiatives to coordinate investments in key foreign mineral processing operations in trusted trading partners (e.g., Mexico, Canada)
  - Adjusting import tariff structures with nations critical to the global mineral supply, such as Australia, Chile, and the Democratic Republic of the Congo, to promote import of minerals as feedstock for U.S.-based mineral processing capacity

Battery material, cell, and powertrain manufacturing: The U.S. lags in this segment, with the majority of investment and innovation occurring in East Asia. However, the U.S. is well positioned in upstream battery material innovation, with leading researchers and strong battery chemistry patent activity, providing a major opportunity to drive commercialization. The U.S. is behind China, Japan, South Korea in patents, and second in publications, but domestic research has a comparably higher impact, trending upstream toward battery material and chemistry innovations. Primary challenges to address include:

Challenge C: U.S. players face significant battery manufacturing supply chain risks. Battery production is highly concentrated in East Asia, with the largest three companies (CATL, LG, and Panasonic) capturing ~70% of global market share. Such a high degree of concentration opens downstream U.S. players to significant supply chain risks and limits potential for competitive advantage for exports. Selection of **potential actions**:

- Promote growth of a domestic battery manufacturing industry: Creating economic parity with larger, at-scale producers in Asia may be accomplished with policies which support the growth of emerging players. Example levers may include
- Enable domestic battery manufacturers to achieve scale: Economics in battery manufacturing are significantly impacted by supply chain collocation and production scale. Supplementing private capital with more patient federal investment can be impactful in accelerating industry growth. Example levers may include:

  - Expand access to federal investments (e.g., loan guarantees, grants) with a focus on scaling battery manufacturing, prioritizing U.S.-based entrants, and new technologies
  - Incentivize collocation centers, or "battery cities", for mineral processers, battery input material producers, and cell/pack manufacturers (e.g., leverage favorable zoning, permitting, grants, or localized tax incentives)

OEM: The U.S. has a strong legacy automotive industry, but no clear right-to-win today in EVs as Asian and European automakers invest heavily in manufacturing automation to improve operational efficiency and reduce costs. Private sector EV OEM investment in China leads the U.S. by over 50% as new startups scale to meet domestic demand, and the U.S. is fifth globally in EV OEM patents. Primary challenges to address include:

Challenge D: U.S. players face significant battery manufacturing supply chain risks. As seen in car market disruptions throughout 2021 and 2022, U.S. manufacturers are highly dependent on semiconductors which are largely produced abroad, particularly in East Asia. Limited access to critical subcomponents can be a major inhibitor of U.S. player competitiveness, both to maintain leadership in domestic markets as well as building a dominant position in exports. Potential actions for the U.S. to build competitive advantage include:

- Encourage onshoring of semiconductor production: Expanding efforts to rapidly onshore semiconductor production is important to EV supply chain security as the chip demand per unit continues to grow, and the large EV market can also be leveraged as a catalyst for this effort. Example levers may include:
  - Expand access to financing for capital-intensive foundry manufacturing facilities to support building domestic manufacturing capacity (e.g., low-interest loan guarantees, grants, or tax credits)
  - Create incentives for U.S.-made chips (e.g., incentives for EV manufacturers that integrate U.S.-made chips into final EV products)

Challenge E: Shifting requirements for a skilled workforce. Although the U.S. has a strong traditional automaker supply base & accompanying workforce that will be powerful in EV transition, maintaining competitiveness abroad will require increasing amounts of automation to manage costs. Though EVs therefore have lower assembly requirements vs. ICE automobiles, line labor will need retraining and new skilled engineers and technicians will be needed to design, build, and maintain the assembly lines of the future. Selection of **potential actions**:

- Expand the EV workforce: Building a robust base of highly skilled labor that can fuel the EV innovation ecosystem, alongside transitioning a legacy automotive workforce while protecting domestic jobs, will be important to supporting the industry. Example levers may include:
  - Support training and upskilling programs for automotive production and maintenance workers to build an EV-capable workforce (e.g., creating EV course materials for junior colleges, sponsoring training programs for high-skill EV-relevant capabilities)
  - Reform immigration policy to increase access to battery manufacturing skill sets (e.g., create new quotas for EV-critical jobs)

Challenge F: U.S. lags China manufacturing capacity and automation investment. Chinese investments outpace the U.S. by ~50% in EV OEM manufacturing capacity over past 4 years as diverse Chinese manufacturers rapidly scale to meet domestic market demand. Although both

Federal and State governments have implemented EV purchase incentives to drive domestic U.S. EV adoption, including the Federal EV Tax Credit, the investment size is outpaced by similar policies in China, which allocated ~$6 B in the 2022 fiscal year budget for NEV purchase subsidies. Selection of **potential actions**:

- Scale domestic manufacturing: Incentivize growth in domestic manufacturing capacity through financing access and streamlined permitting. Example levers may include:
    - Expand financing access to small-scale EV companies operating in new market segments, such as trucking (e.g., public loan guarantees, grants)
    - Leverage localized incentives and permitting policies to drive collocation of OEMs alongside aforementioned "battery cities"
- Maintain and grow EV demand: Increasing demand is a less important factor in this industry as supply is currently outstripped, however continuing to support widespread adoption will help grow the domestic industry. Example levers may include:
    - Reduce the green premium through tax credits (e.g., extending the consumer purchase tax credit)
    - Shift large-scale domestic federal fleets (e.g., DoD, USPS, DoT) to battery-electric powertrains
    - Invest in critical infrastructure such as a nationwide charging network and relevant grid expansion to drive adoption and justify private investment in domestic EV manufacturing capacity
- Software and after-sales services: The U.S. has a strong competitive lead in advanced automotive software and service segments, including autonomous and connected vehicle technology. Major leads in IP and investment activity reflect a rapidly maturing ecosystem with leading providers beginning commercial deployments. Private investment in the U.S. totals ~$40B over the last four years; the next largest market, China, saw $11B invested over the same period.

Challenge G: Maintain U.S. leadership in software and aftersales services. Although the U.S. currently enjoys a significant lead in the aftersales services segment in the near term, long-term growth of competitors in East Asia may soon make this a contested area. Further, advanced software including connected vehicles and ADAS / Autonomous Vehicle (AV) features are becoming increasingly included in the EV consumer value proposition. Innovative, well integrated platforms can strongly differentiate product offerings, and companies & countries with robust & agile software capabilities are better positioned to capture share in the overall EV OEM market. Selection of **potential actions**:

- Support AV innovation: Continue to invest in U.S. leadership in autonomous vehicle research, development, and deployment. Example levers may include:
    - Expand funding of R&D programs related to next-generation vehicle technologies, including AI, ML, sensors, and semiconductor research
    - Develop standardized policy guidelines and regulations around AVs that States and municipalities can adopt (e.g., to create safe testing environments, to establish performance targets for commercial applications)

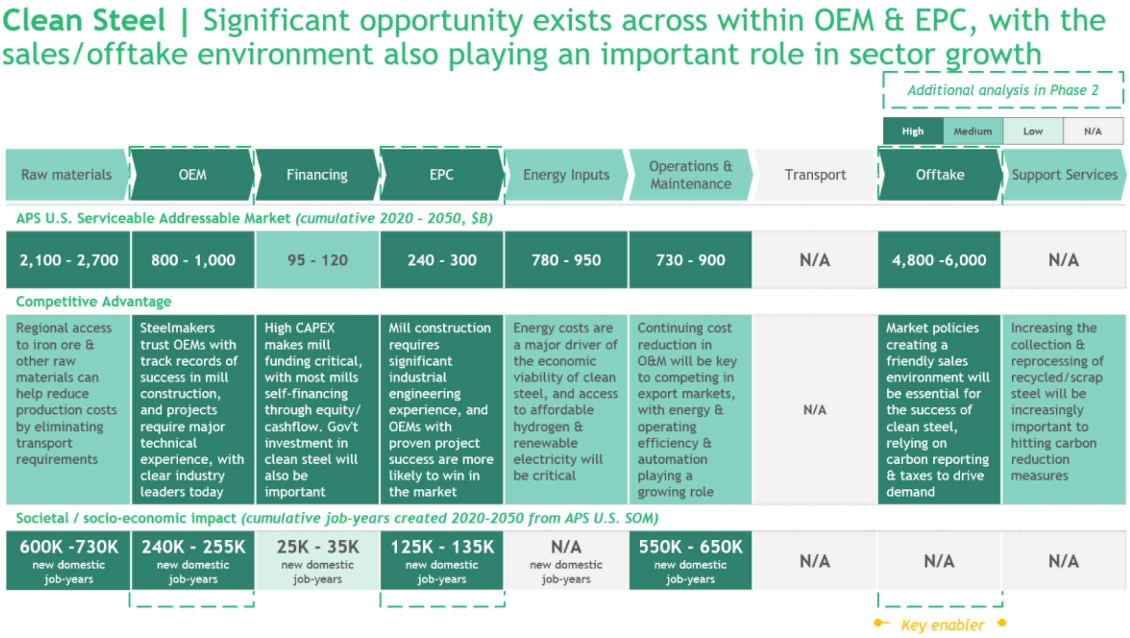
5 Clean Steel

Steelmaking accounts for nearly 10% of the global energy sector's carbon emissions [IEA] and is considered a hard-to-abate sector due to the technical challenges and heavy capital investments involved. Clean Steel describes a set of techniques that combine efficiency improvements, renewable energy, furnace technologies, and low/no-carbon substitute fuels and feedstocks to reduce emissions. The major approaches include:

- Direct reduced iron (DRI) fueled primarily by green hydrogen, coupled with an electric arc furnace (EAF) for steel production (hydrogen DRI-EAF)
- Direct reduced iron fueled by natural gas (or coal) alongside CCUS, coupled with an electric arc furnace for steel production (DRI-EAF)
- Installing carbon capture and sequestration/usage systems to capture emissions from traditional blast furnace-basic oxygen furnace facilities (BF-BOF)

Additional pathways exist, including smelting-reduction BOF (SR-BOF) and CCUS, and emerging technologies such as molten oxide electrolysis (MOE), but these are not expected to play a major role in the near-term decarbonization pathway for the industry through 2050. Steel is also one of the most highly recyclable materials, and production via scrap-electric arc furnace (scrap EF) is a major clean steelmaking pathway. A detailed view of the clean steel value chain assessed in this study is included in appendix page 162.

5.1 Overview of value chain segments considered for this study



Clean Steel | Significant opportunity exists across within OEM & EPC, with the sales/offtake environment also playing an important role in sector growth

Additional analysis in Phase 2

High	Medium	Low	N/A

	Raw materials	OEM	Financing	EPC	Energy Inputs	Operations & Maintenance	Transport	Offtake	Support Services
APS U.S. Serviceable Addressable Market *(cumulative 2020 - 2050, $B)*	2,100 - 2,700	800 - 1,000	95 - 120	240 - 300	780 - 950	730 - 900	N/A	4,800 -6,000	N/A
Competitive Advantage	Regional access to iron ore & other raw materials can help reduce production costs by eliminating transport requirements	Steelmakers trust OEMs with track records of success in mill construction, and projects require major technical experience, with clear industry leaders today	High CAPEX makes mill funding critical, with most mills self-financing through equity/ cashflow. Gov't investment in clean steel will also be important	Mill construction requires significant industrial engineering experience, and OEMs with proven project success are more likely to win in the market	Energy costs are a major driver of the economic viability of clean steel, and access to affordable hydrogen & renewable electricity will be critical	Continuing cost reduction in O&M will be key to competing in export markets, with energy & operating efficiency & automation playing a growing role	N/A	Market policies creating a friendly sales environment will be essential for the success of clean steel, relying on carbon reporting & taxes to drive demand	Increasing the collection & reprocessing of recycled/scrap steel will be increasingly important to hitting carbon reduction measures
Societal / socio-economic impact *(cumulative job-years created 2020-2050 from APS U.S. SOM)*	600K -730K new domestic job-years	240K - 255K new domestic job-years	25K - 35K new domestic job-years	125K - 135K new domestic job-years	N/A new domestic job-years	550K - 650K new domestic job-years	N/A	N/A	N/A

Key enabler

Figure 5.1 - Clean Steel Value Chain Prioritization Results

In assessing areas for deep-dive analyses, the study focused on three key areas:

- **OEM**: The manufacturing of clean steelmaking equipment including DRI reactors compatible with natural gas (stopgap) and hydrogen, requires the highest technical expertise, particularly as emerging steelmaking techniques such as hydrogen-based DRI and molten oxide electrolysis begin to see commercial deployments over the next decade

- **EPC**: EPC for clean steelmaking, either as new construction or retrofits to existing facilities, was also prioritized because the ability to coordinate on-time, on-budget installations can be a partnership differentiator for mills or OEMs. This can include either new mill construction or retrofits with new furnace technologies or CCUS systems

- **Offtake**: While not a key differentiating segment in terms of private sector movement, in this commodity industry the most impactful policy interventions must be demand-side, focused on creating a clean steel market and price parity with traditional products

5.2 Size of the opportunity in domestic market and exports

The domestic market is expected to be the largest opportunity for U.S. clean steelmakers, with Canada and Mexico as the primary export opportunities. OEMs have the opportunity to target other major and emerging steel-producing regions including Europe, Japan, South Korea, and India. The U.S. Serviceable Addressable Market (SAM) for clean steel is expected to be $3-5.4T in cumulative value through 2050. The U.S. domestic market is expected to reach ~$30B by 2050, with Canada and Mexico, collectively, representing a ~$20B additional market opportunity. Notably, these figures vary significantly across scenarios, with the NZE representing a nearly 300% and 70% upside over the STEPS and APS scenarios, respectively, given the high impact of policy in this sector. Together, these three countries represent the U.S. SOM in the offtake market given the prohibitive economics of intercontinental steel trade. India also presents an exciting OEM/EPC opportunity given it will be the major growth center for steel production globally over the next 30 years. By 2050, India will represent ~35% of the U.S. SAM in those segments.

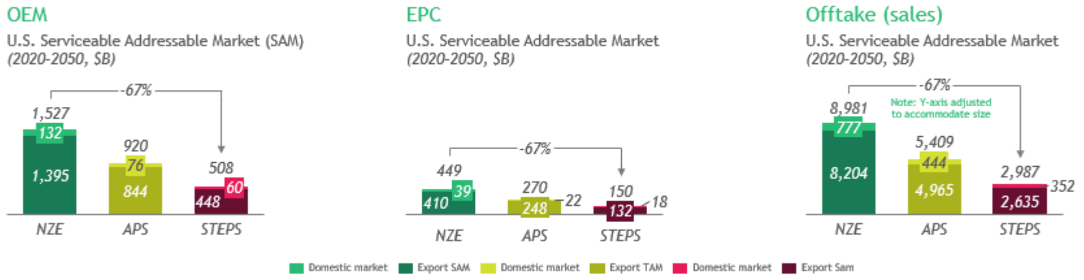


Figure 5.2 - Cumulative Deployment Potential by Priority Market

Across segments, the Chinese market was excluded from the U.S. SAM given the unlikelihood of Chinese mills to procure equipment from U.S. manufacturers amidst public and private pressure around domestic sourcing, and limited exports of steel to China today. Russia was also excluded given the recent shutdown of trade relations amidst the invasion of Ukraine and limited steel trade prior to 2022. Important foreign countries and regions broken out in this analysis are further detailed in the tables below.

U.S. Serviceable Obtainable Market (SOM) for clean steel is estimated to be about 5-15% of the total global market. The lower bound or business-as-usual for SOM is based on the average U.S. share of global steel production from 2015-2020. The upper bound or market leader position is 15% which represents capturing the entirety of the North America market, based on its portion of the global steel market in 2021. Exports to Canada and Mexico, which make up ~90% of U.S.

steel exports[5], heavily influence U.S. SOM. Aligning these main export partners on emissions intensity standards for clean steel will be critical for the U.S. to capture as much of the North American steel market as possible. A potential limitation for U.S. SOM is Canada, with increasing leadership in steel decarbonization, scaling its domestic clean steel capabilities and relying less on imports from the U.S. The U.S. can also increase its SOM by capturing more of the domestic steel market, possibly through incentives for purchasing lower emissions intensity steel.

Priority Markets	**Segments included in SAM**	**Relevant drivers for breakout**
Europe	OEM EPC	• Private and public initiatives across Europe are leading the way in demonstration plants and small-scale initiatives for H2-based DRI-EAF clean steel production, and the region will likely be a leader in clean steel investment and adoption • Similar to Japan, there are several prominent OEMs that will likely capture much of the European market, but opportunities still exist for U.S. exports and partnerships • The E.U. CBAM will likely further accelerate clean steel transition
India		• India is expected to experience a massive growth in domestic steelmaking, with a nearly 4x increase in output though 2050 • Despite slower adoption of decarbonization policies, this expansion in growth and gradual momentum towards reducing industry emissions is expected to drive significant demand for new clean steelmaking equipment • Most growth is expected to come in later years, with 45% cumulative market value in 2045-2050
Japan & South Korea		• Japan and South Korea together account for ~8% global steel product and 2x US domestic steel production • Private industry and policymakers have set ambitions to decarbonize steel production, and are set to be leaders in the space as they focus on scaling H2-based DRI-EAF • As local companies are leaders in the OEM and EPC space, there may be limits to the SOM. However, there is greater potential for the US to break into clean steel due to trade and technical partnerships
Canada & Mexico	Offtake	• Canada and Mexico each account for ~45% of U.S. steel exports • Due to shipping economics and robust North American trade agreements, rail and transportation networks,

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[5] Steel Exports Report: United States

Priority Markets	Segments included in SAM	Relevant drivers for breakout
		and economic partnerships, this trend will likely continue as production shifts to clean steel

Inaccessible Markets	Excluded Segments	Relevant drivers for exclusion
China	• OEM • EPC • Offtake	• Despite being a major steel producer, Chinese steel producers operate largely independently from Western players and do not use Western-made equipment. Furthermore, over 90% of steel production is through BF-BOF steelmaking and will likely rely more on CCUS retrofits vs. any U.S.-made DRI-EAF equipment • Despite being a top-10 export market for U.S. steel in 2019, China meets the overwhelming proportion of its steel demand with domestic production, and U.S. exports to the country are rapidly shrinking (~30% reduction in 2018-2019 alone). Due to the concentration of exports in NA, exports to China only cumulatively account for ~1% of overall export value • Public and private momentum is pushing for greater domestic control of the supply chain
Russia		• Russian steel producers have traditionally partnered with a limited set of U.S. equipment OEMs in the construction of DRI-EAF steel mills, however due to current trade restrictions and sanctions, these activities have been halted and there is significant uncertainty about the potential for any future OEM market. This market is being considered as unavailable given current outlooks, but a governmental leadership change could reopen avenues for the export of clean steelmaking equipment • The Russian market is historically not a significant export market for U.S. steel, and due to ongoing geopolitical tension fueled by the war in Ukraine, Russian imports of US-made steel will continue to decline

Table 4.1 - Detail on independently modeled countries & regions for inclusion

5.3 Segment level analysis

5.3.1 OEM

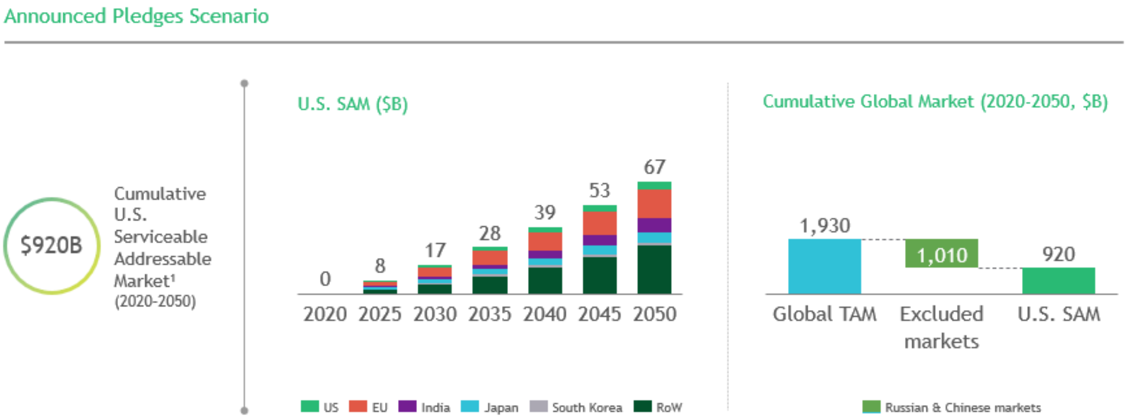


Figure 5.3 - OEM annual market value, Announced Pledges Scenario (APS)

- The EU is the largest single region in both the STEPS and APS scenarios, with the clearest and most aggressive regionwide climate ambitions, totaling 25% of the SAM in 2050 in the APS
- The NZE sees India becoming a massive growth center for clean steelmaking as its domestic steel production rapidly expands. Driving India to increase climate targets and laying a trade agreement foundation for exchange of OEM equipment could be a prudent investment in this export market
- The U.S. margin pool is comparatively small at just 8-11% of total. But given the relative inaccessibility of other markets due to local players or trade challenges, leveraging the domestic margin pool may be critical to building an industry capable of exports

5.3.2 EPC

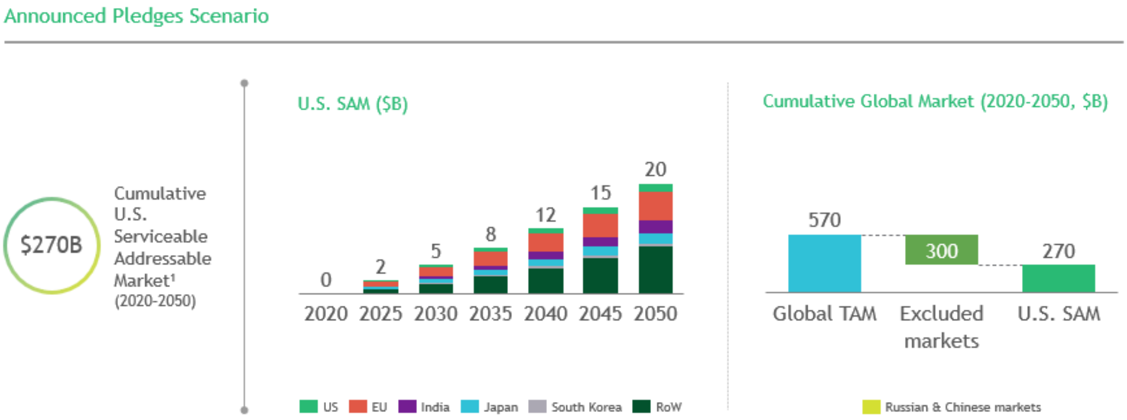


Figure 5.4 - EPC annual market value, Announced Pledges Scenario (APS)

- EPC is a comparably small segment, with the overall SAM only reaching ~$11B and ~$30B in the STEPS and NZE, respectively
- The EPC market largely mirrors the larger OEM segment, with the EU as the clearest export opportunity at ~25% of the overall market and India representing a major growth center
- Significant value will be captured by local contractors, particularly in markets with significant experience handling the precursors to steelmaking equipment such as DRI-EAF (e.g., Japan, Europe)
- More emerging and rapidly growing markets including India may need greater imported EPC services
- The overall SAM margin pool in EPC is small at only a cumulative $12-36B across scenarios, and much of this value will be captured by the local market

5.3.3 Offtake

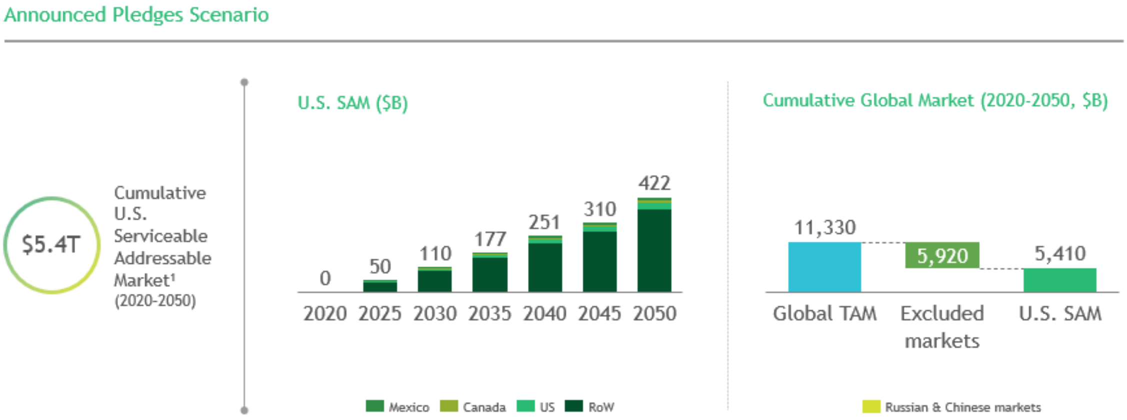
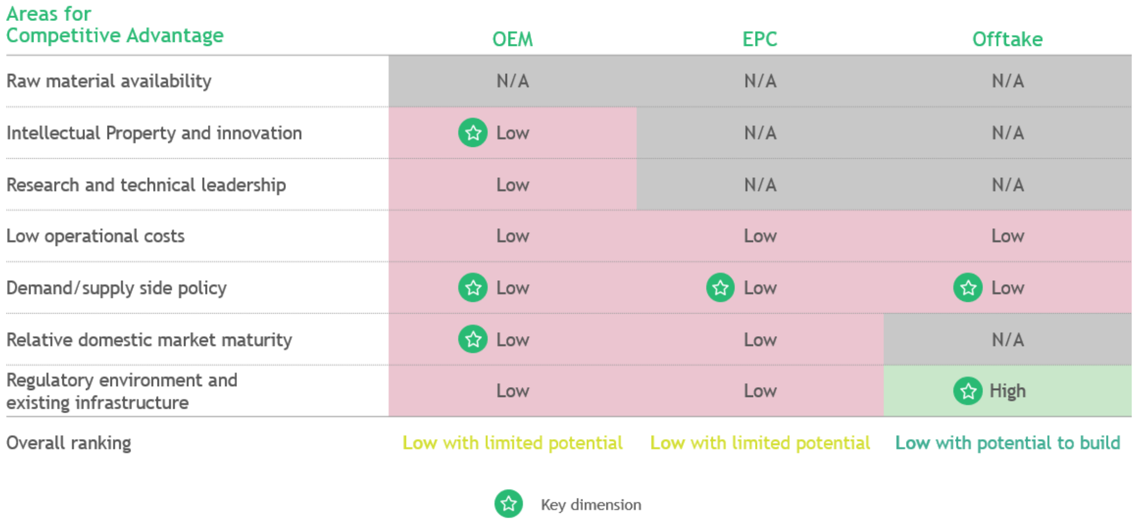


Figure 5.5 - Offtake annual market value, Announced Pledges Scenario (APS)

- Despite a large overall offtake segment, just 12-15% of the global SAM opportunity is within North America, where the U.S. is most likely to win share
- The wide 3x delta between STEPS and NZE scenarios reflects the high sensitivity to climate targets, as steel will likely be one of the last sectors to be abated
- The U.S. represents the largest single-country opportunity, and the domestic market should be a focus to build scale in U.S. clean steel production
- Overall clean steel market is a significant profit opportunity, with up to $1T in cumulative pool
- Margins in clean steel production are still nascent and highly subject to public policy incentives and energy prices

5.4 Overview of competitiveness



Areas for Competitive Advantage	OEM	EPC	Offtake
Raw material availability	N/A	N/A	N/A
Intellectual Property and innovation	☆ Low	N/A	N/A
Research and technical leadership	Low	N/A	N/A
Low operational costs	Low	Low	Low
Demand/supply side policy	☆ Low	☆ Low	☆ Low
Relative domestic market maturity	☆ Low	Low	N/A
Regulatory environment and existing infrastructure	Low	Low	☆ High
Overall ranking	Low with limited potential	Low with limited potential	Low with potential to build

☆ Key dimension

Figure 5.6 - Current U.S. competitive advantage across key areas, by segment

Figure 5.6 summarizes U.S. competitive advantage across the 3 prioritized segments for clean steel. Current U.S. competitive advantage is classified as “High” or “Low” (see Figures 3.1 and 10.3 for methodology), with a summary ranking in the final row that is used for plotting in Figure 10.12. Recommendations focus on key dimensions of competitive advantage, denoted by the green star, because these dimensions must be unlocked to create durable competitive advantage. Explanations of competitive advantage ranking and key dimensions by value chain segment can be found in the main text.

- Intellectual property & innovation (Low): Clean steel OEMs span a variety of clean steel technology, including EAF, DRI, CCUS, and emerging steelmaking technology. China is the clear leader across most EAF, DRI, and CCUS, with ~3.5x more patent activity than the EU, who is 2nd in patent activity. The U.S. is 3rd, at 40% of patent production of the EU for sustainable steel. For emerging molten oxide electrolysis technology, the U.S. has a small lead at 2x China’s patent activity, but there is low total patent activity in this segment

- Demand/supply side policy (Low): Demand side policies are critical to encourage sales of clean steel, as it will be a more expensive alternative for a commodity product. The EU leads demand side policies, with moves to implement a strong carbon border adjustment mechanism (CBAM) that will incentivize the growth of its regional clean steel industry and encourage sustainable steelmaking from its major import partners (e.g., Turkey, Russia, and Ukraine[6]). At a much smaller scale, some public programs in the U.S., like the Buy Clean Task Force, could be used to increase demand for clean steel. Overall, the U.S. has no dedicated clean steel demand policies. However, the 45Q tax credits by the U.S. can act as a potential supply side driver clean steel, by incentivizing CCUS at steel facilities

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[6] Steel Imports Report: European Union

- Relative domestic market maturity (Low): Private investments in clean steel are led by China, though the U.S. has notable investment in emissions reduction and carbon capture technology. Importantly, most East Asian (particularly Chinese) investments are in large part driven by public initiatives, internal corporate investments, or state-owned corporations, so are less visible in private investment assessments. The leading patent activity of Chinese (~3.5x the next leader) and strong patent activity of South Korean (~8% of China) and Japanese (~4% of China) steelmakers suggest major investment in these markets. Canadian steelmakers have made a commitment to reach net-zero by 2050, suggesting a rapid expansion in future investment in this market. U.S. domestic OEMs largely operate in-house for major steelmakers, limiting potential export of technology and expertise

- Regulatory environment & existing infrastructure (High): The U.S. is the main source of steel for North America, providing ~40%[7] and ~30%[8] of Canadian and Mexican steel imports, respectively. Given the high existing proportion of scrap based EAF production, the U.S. is one of the lowest carbon intensity producers globally today, making it well-positioned for the clean steel transition. U.S. domestic steel producers can then benefit from U.S. and international carbon border adjustment mechanisms or other emissions-related subsidies/incentives, as other steel producers will need to invest significant capital to come into emissions intensity parity with U.S. steel.

5.5 Summary of findings

Commercial-scale deployment of clean steel in the U.S. faces challenges technology-wide and at the level of each of the three prioritized value chain segments. Though the U.S. has an advantage by already having low emissions intensity in steel production, it faces challenges of developing a strong domestic market and export competitiveness, especially in the absence of strong demand side policies. A domestic market with robust demand is necessary to further increase cost efficiencies in clean steel production in the U.S. and then enable greater export of clean steel.

Technology-wide: The U.S. today is one of the lowest carbon-intensity steel producers globally due to its high proportion (~70%) of electric arc furnace (EAF) production (majority through scrap route), ranking 4th lowest in carbon intensity amongst major producers and 60% lower than Chinese producers[9]. As a result, the U.S. has domestic expertise in cleaner steelmaking including direct reduced ironmaking (DRI), EAF-based steel production, and carbon capture. However, a lack of dedicated OEMs, clear technical advantage, or carbon tax mechanisms results in a weak U.S. position as a global leader/exporter.

Challenge A: The higher price of clean compared to traditional steel and the commodity nature of the steel market is likely to limit demand for clean steel. Low demand will discourage steelmakers from investing in clean steel technology. This could slow progress for emerging or commercially nascent technology, like molten oxide electrolysis and CCUS, and limit cost reductions achievable via learning and economies of scale. The long lifetimes of legacy furnace technologies, 20-30 years[10], requires that the steel industry move within the next five to eight years in order to meet a 2050 emissions reduction target, including disincentivizing the re-lining

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[7] Steel Imports Report: Canada

[8] Steel Imports Report: Mexico

[9] How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities

[10] Decarbonizing the Steel Sector in Paris – Compatible Pathways

of the nine U.S. domestic BF-BOF furnaces. Potential actions for the U.S. to build competitive advantage include:

- Grow demand for clean steel, including low-carbon intensity U.S. steel produced today: Given the commodity nature of steel, it will be important to encourage demand for clean steel vs. cheaper traditional steel. Potential actions to implement this solution include:
    - Carbon border adjustments could support development of a domestic clean steel industry. Mechanisms that bring clean steel to near price parity with traditional steelmaking can accelerate commercial viability and deployment of innovative technologies like CCUS and molten oxide-electrolysis. A border adjustment can also protect U.S. steel players, given the low emissions intensity for U.S. steel production.
    - Establish federal procurement targets and support emissions intensity standards to foster reliable clean steel demand

Challenge B: A significant increase in the availability of energy inputs is needed to facilitate a cleaner steel transition, including in renewable electricity and 100-200x growth in green hydrogen production. Currently, hydrogen production from renewables is 3 - 4x more expensive than grey hydrogen production using fossil fuels, according to BCG cost models, creating a green premium. Costs for renewable and low-carbon energy must decrease, while access increases to support a more cost-competitive clean steel industry. Selection of **potential actions**:

- Prioritize grid decarbonization: While not the immediate focus of this section, the immense electricity requirements of clean steel production for both heat and hydrogen will only increase the need for green sources of power Given the high penetration of EAFs in the U.S. (~70%), grid decarbonization efforts will further reduce the carbon emissions intensity of domestic steel production. Selection of potential actions:
    - Encourage development of low- or no-carbon electricity supply
    - Support streamlined processes for grid access and permitting

- OEM: Despite having steelmakers with low carbon impact today, there are few strong OEMs within the U.S. across the clean-steel segment. The U.S. is notably behind China and the EU in IP and research activity, with only ~10% and ~40% of sustainable steel patents produced by China and the EU, respectively. The U.S. does have a significant presence in the carbon capture segment as the 2nd leading patent producer, though China produces four times more CCUS in steel patents. This advantage in carbon capture may make the U.S. a potential exporter of those technologies to countries that rely on more traditional, carbon-intensive BF-BOF integrated steel production.

Challenge C: High costs associated with innovative technology and pilots can limit the progress of emerging OEMs, which is exacerbated by the steel industry being an incumbent-dominated sector. Emerging technologies like molten oxide electrolysis and 100% hydrogen-based DRI could create significant energy savings and emissions reductions if they are able to reach commercial viability. However, a lack of support for innovation could slow development of these technologies and the clean steel transition. Selection of **potential actions**:

- Support emerging OEMs as technologies mature: Supporting emerging players and technologies will be important to maintaining innovation in this highly sticky and incumbent-dominated sector. Example levers may include:
    - Provide mechanisms to ensure investments of smaller steelmakers to transition to clean steel technology are recouped (e.g., low-cost loan programs)

    - Encourage emerging steelmaking technology innovation in the U.S. (e.g., grant and loan guarantee programs)

Challenge D: Though the U.S. has a notable presence in CCUS, the lack of commercial deployments of CCUS in steelmaking today leave an opportunity for other nations to capture market share in this emerging sector. The lack of largescale deployment combined with the tendency for existing large steelmakers to implement clean steel technology at scale create a disadvantage for smaller steelmakers to shift towards lower emissions technology. This challenge is applicable to both OEM and EPC. Selection of **potential actions**:

- Continue support for growing the domestic CCUS industry: To maintain U.S. leadership in CCUS, it will be important to continue supporting domestic CCUS development, especially in applications for steelmaking. Example levers may include:
    - Reduce investment risk for CCUS system development by steelmakers (e.g., tax credits, cost-sharing subsidies)
    - Encourage existing CCUS-support investments to incorporate steelmaking decarbonization (e.g., IIJA)

EPC: Existing U.S. steelmakers have strong in-house EPC capabilities due to their experience constructing EAF mini mills. However, steelmakers are unlikely to market this competence to competitors. Additionally, the market potential of this segment is low and there are few dedicated U.S. EPCs. Some potential exists to expand on the U.S. lead in point-source CCUS emissions activity by building corresponding EPC capabilities and exporting to foreign markets. **Challenge D** is also applicable to EPC and selection of **potential actions**:

- Support infrastructure critical to clean steelmaking project development: Investment in the critical supporting infrastructure for clean steelmaking will be important to developing a commercial ecosystem. Example levers may include:
    - Encourage the buildout of domestic CCUS transportation infrastructure (e.g., grants through SCALE Act, DoE CarbonSAFE)
    - Support development of centralized hydrogen infrastructure and collocated hydrogen-based DRI steelmaking facilities (e.g., production tax incentives)

Offtake: The U.S. has a gap in the offtake segment with no major incentives or subsidies for clean steelmaking. Despite relatively localized initiatives such as the First Movers Coalition and Buy Clean Task Force, the U.S. has no comprehensive carbon-adjustment or clean steelmaking subsidies. In contrast, the European Commission is preparing to launch a CBAM that will begin to incentivize clean steelmaking. However, a low carbon intensity today makes the U.S. an advantaged exporter if other nations, particularly Canada or Mexico, implement carbon adjustments.

Challenge E: A lack of standards for CO_2 emissions from steel production and barriers to adoption could limit potential offtake of U.S. steel to export partners, especially those with increasing emissions reductions goals. Canada, which currently imports ~45% of U.S. steel exports[11], has pledged to reach net zero emissions by 2050, including a pledge by Canadian steelmakers to meet the same goal. This underscores the need for the U.S. to align on standards of steel emissions intensity with key trading partners to ensure offtake of U.S. steel. Offtake of

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[11] Steel Exports Report: United States

clean steel is also limited by higher relative costs and a lack of processes to credit clean steel use. Selection of **potential actions**:

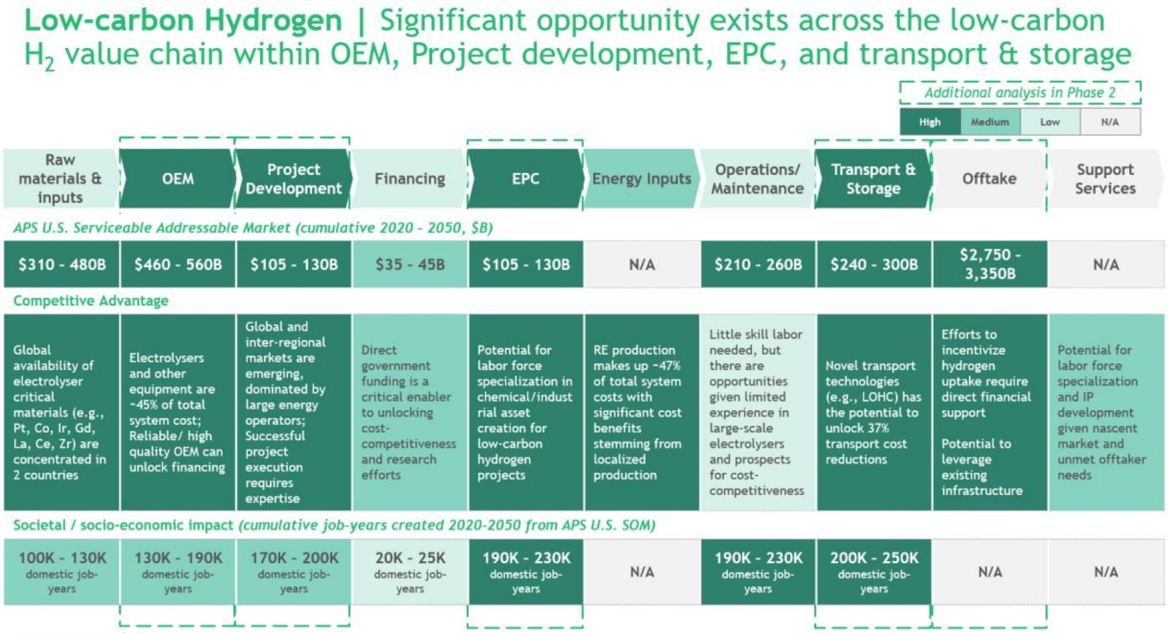
- Support development of standardized, public carbon accounting: A universal carbon accounting system can enable successful procurement strategy or carbon adjustment and will also be important to certifying private-sector initiatives. Example levers may include:
    - Support development of standardized carbon-tracking mechanisms to monitor and certify carbon intensity of domestic and imported steel production (e.g., Environmental Product Declarations, EPD)
    - Remove adoption roadblocks: De-risk companies transitioning supply chains to clean steel (e.g., initial subsidies) and encourage private sector clean steel offtake. Example levers may include:
    - Encourage standards organizations to incorporate clean steel into standardized documentation and acceptance of clean steelmaking (e.g., within federal codes for broad applications)
    - Reduce costs for clean steel adoption (e.g., cost-sharing programs)

6 Low-carbon Hydrogen

Low-carbon hydrogen (H_2) has many potential applications for a low-carbon/net-zero energy system, including fertilizer creation (e.g., ammonia, methanol), as a feedstock for synfuels or as a low-carbon fuel source, and in industrial processes like direct reduction of iron in clean steel. The generation of heat energy by burning hydrogen (H_2) yields a byproduct of water and, importantly, no CO_2 emissions. However, some NO_x is emitted when N_2 (mixed in the H_2 and O_2) is burned, so there's a potential need to also trap NO_x emissions[12].

Low-carbon H_2 should be defined and prioritized for use based on a lifecycle analysis (LCA) of its carbon intensity, rather than restricting based on color designations. Green hydrogen is made using renewable energy (RE) and is generally prioritized over blue H_2 due to the commodity prices of natural gas. Blue hydrogen is produced using natural gas coupled with CCUS of generated CO_2. For blue H_2 to achieve comparable carbon intensity to renewable H_2, its production process must include mitigation of upstream fugitive emissions of methane and effective carbon capture of generated CO_2 with permanent carbon storage. Low-carbon H_2 production can include other technologies, such as methane pyrolysis (turquoise) and nuclear-powered (pink) electrolysis, but these technologies are not explicitly included in this report. A detailed view of the low-carbon value chain analyzed is included in appendix page 92.

6.1 Overview of value chain segments considered for this study



Low-carbon Hydrogen | Significant opportunity exists across the low-carbon H_2 value chain within OEM, Project development, EPC, and transport & storage

Additional analysis in Phase 2

High	Medium	Low	N/A

Raw materials & inputs	OEM	Project Development	Financing	EPC	Energy Inputs	Operations/ Maintenance	Transport & Storage	Offtake	Support Services
APS U.S. Serviceable Addressable Market (cumulative 2020 - 2050, $B)									
$310 - 480B	$460 - 560B	$105 - 130B	$35 - 45B	$105 - 130B	N/A	$210 - 260B	$240 - 300B	$2,750 - 3,350B	N/A
Competitive Advantage									
Global availability of electrolyser critical materials (e.g., Pt, Co, Ir, Gd, La, Ce, Zr) are concentrated in 2 countries	Electrolysers and other equipment are ~45% of total system cost; Reliable/ high quality OEM can unlock financing	Global and inter-regional markets are emerging, dominated by large energy operators; Successful project execution requires expertise	Direct government funding is a critical enabler to unlocking cost-competitiveness and research efforts	Potential for labor force specialization in chemical/industrial asset creation for low-carbon hydrogen projects	RE production makes up ~47% of total system costs with significant cost benefits stemming from localized production	Little skill labor needed, but there are opportunities given limited experience in large-scale electrolysers and prospects for cost-competitiveness	Novel transport technologies (e.g., LOHC) has the potential to unlock 37% transport cost reductions	Efforts to incentivize hydrogen uptake require direct financial support Potential to leverage existing infrastructure	Potential for labor force specialization and IP development given nascent market and unmet offtaker needs
Societal / socio-economic impact *(cumulative job-years created 2020-2050 from APS U.S. SOM)*									
100K - 130K domestic job-years	130K - 190K domestic job-years	170K - 200K domestic job-years	20K - 25K domestic job-years	190K - 230K domestic job-years	N/A	190K - 230K domestic job-years	200K - 250K domestic job-years	N/A	N/A

Source: BCG Analysis

Figure 6.1- Clean Hydrogen Value Chain Prioritization Results

In assessing areas for deep-dive analyses, the study focused on four value chain segments:

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[12] Optimising Air Quality Co-Benefits in a Hydrogen Economy: a Case for Hydrogen-Specific Standards for NO_x Emissions

- **OEMs** were prioritized because of their central role in manufacturing and designing electrolysers, compressors, and water purifiers for green H_2, and manufacturing reformer and Carbon capture, utilization, and storage (CCUS) technology for blue H_2. There is strong potential for defendable and important IP in developing electrolysers without rare metals.

- **Project development** is also strategically important for scaling and logistics, as is **transport and storage**. This segment holds significant cost-reduction potential via access to modern pipeline infrastructure, import/export facilities, and skilled expertise. Further, with rapidly scaling H_2 production globally, an early-mover advantage could enable export of project development expertise and novel technologies for transport and storage.

- **Offtake** is also a potential source of competitive advantage because H_2 can be used as a feedstock in the production of ammonia, cement/steel or in oil refining; H_2 in fuel cells can be used for a multitude of applications, including EVs, houses, and portable power. H_2 also has industrial use potential for heat and energy generation and storage. Incentivizing H_2 in the short term is critical for cost reduction and scaling; countries increasing H_2 uptake can develop competitive advantage across the value chain via learnings (greater efficiency and lower cost) and sales agreements.

- **Raw Materials** were not prioritized in this study because the critical metals used in electrolysers are geographically concentrated in other countries. And while investment is critical in the near future for innovation and enabling low-carbon H_2, **financing** in the long term is likely to follow more traditional models and is thus not a competitive advantage. **Energy inputs** are key enablers, so were also deprioritized, as were **EPC** and **O&M** (small and local market sizes).

6.2 Size of the opportunity in domestic markets and exports

The U.S., South Korea, and the EU are expected to be the largest opportunities for U.S. H_2 players. The U.S. Serviceable Addressable Market (SAM) in APS for low-carbon H_2 is expected to be ~$3,900B through 2050 ($320B-$9,900B, STEPS-NZE), reaching an annual capacity of ~6,100 million kg H_2/yr, up from ~3.3 million kg H_2/yr in 2020. The U.S. SAM market in APS will be dominated by the EU market at of ~$1,200B (20 - 1,200B, STEPS-NZE), followed by the U.S. domestic market of ~$350B ($30 – 1,300B, STEPS-NZE), and the South Korea market cumulatively valued at ~$430B ($40 – 750B, STEPS-NZE). Overall, H_2 offtake is by far the largest market opportunity of the value chain segments, making this an important segment for building U.S. competitive advantage.

China was excluded from the U.S. SAM for all prioritized segments because of China's moves to diversify import energy partners and increase domestic energy, Chinese electrolysers dominance in the market for cost-competitiveness and reported violations of IP rights from Western companies in joint ventures.

The Middle East region was also excluded from U.S. SAM for offtake because of a combination of limited policies to incentivize low-carbon H_2 domestic offtake and the region's likelihood to meet the capacity and renewable energy needs for future regional low-carbon H_2 demand.

U.S. Serviceable Obtainable Market (SOM) is expected to be 15-30% of the Total Addressable Market (TAM). The lower end of the range is based business-as-usual where the U.S. maintains the share of global H_2 production from 2014-2018 as a baseline for future market share. The upper end, representing market leadership, is based on the percentage of global H_2 export in 2021 obtained by both Canada & Belgium, the export market leaders.[13] A potential barrier to building and maintaining market share is meeting export partner requirements for low-/zero-carbon H_2. This will be necessary to maintain or secure additional global market share for low-/zero-carbon H_2, as compared to U.S. H_2 production today. If main export partners instead limit the type of low-carbon H_2 that is acceptable, this could significantly lower U.S. export SOM. As an example, the EU Commission's REPowerEU draft indicates that only renewable H_2 will be an acceptable import, thus removing the possibility for other low-/zero-carbon H_2 imports. U.S. SOM also will be influenced by emissions reduction targets that encourage switching to low-/zero- carbon H_2, and the United States ability to develop novel technologies and cost-effective commercial H_2 production.

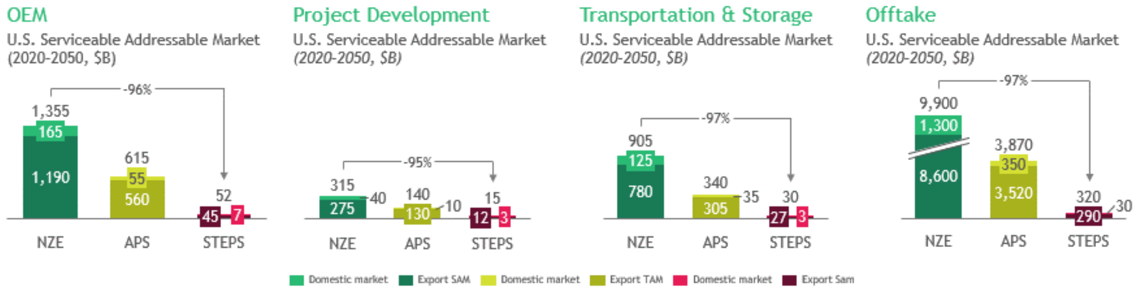

Figure 6.2 - Cumulative Deployment Potential by Priority Market

Priority Markets	Segments included in SAM	Relevant drivers for breakout
EU	• OEM • Project Development • Transport and Storage • Offtake	• The EU is spearheading efforts to define standards and regulations around green H2, with plans for uptake • Significant electrolyser capacity additions through 2050 are expected to drive need for transportation and storage, OEM, and project development services in regions like the EU that are investing in future H2 uptake
Japan		• Japan was one of the first countries to release a national H2 plan (2017) and is publicly funding development of domestic H2 supply chains • Limited domestic production capacity presents an opportunity for the U.S. to supply H2 molecules and derivatives and infrastructure to support the H2 market • - High expected H2 demand in Japan will likely require novel H2 carriers to reduce long-distance transport costs
South Korea		• With limited domestic capacity and aggressive hydrogen targets, South Korea has committed

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[13] Hydrogen exports by country in 2021

Priority Markets	Segments included in SAM	Relevant drivers for breakout
		to importing H2 molecules and derivatives, which the U.S. could provide • Strong future H2 demand suggests South Korea will need novel hydrogen carriers to reduce long-distance transport costs

Inaccessible Markets	Excluded Segments	Relevant Drivers for Exclusion
China	• OEM • Project Development • Transport and Storage • Offtake	• Persistent tensions between China and the U.S. restrict energy imports and have encouraged domestic energy production • Western companies report frequent violations of IP rights in joint venture agreements, which limits the value creation potential of exporting IP to China • Chinese electrolyser manufacturers currently dominate the electrolyser market on cost competitiveness, so would be unlikely to purchase other electrolysers
• Middle East	• Offtake	• Currently, low-carbon H2 demand is low due to limited policies incentivizing domestic offtake, presenting little opportunity • The Middle East region is expected to have the capacity and RE resources necessary to meet any future regional low-carbon H2 demand

Table 5.1 - Detail on independently modeled countries & regions

6.3 Segment level analysis

6.3.1 OEM

- OEM SAM is the second-largest across all segments, driven by the high cost of electrolyser equipment
- U.S. SAM comprises ~80-85% of global TAM, with remaining ~15-20% in inaccessible markets such as China
- Under NZE, OEM undergoes steep ramp-up in the next decade, with peak occurring in ~2030 to reflect aggressive global demand for hydrogen. In subsequent years, market size declines both due to a slowing growth rate and substantial cost reductions in electrolyzer CapEx
- Peak in SAM shifts out to 2035 under STEPS and APS to reflect delayed capacity build-out

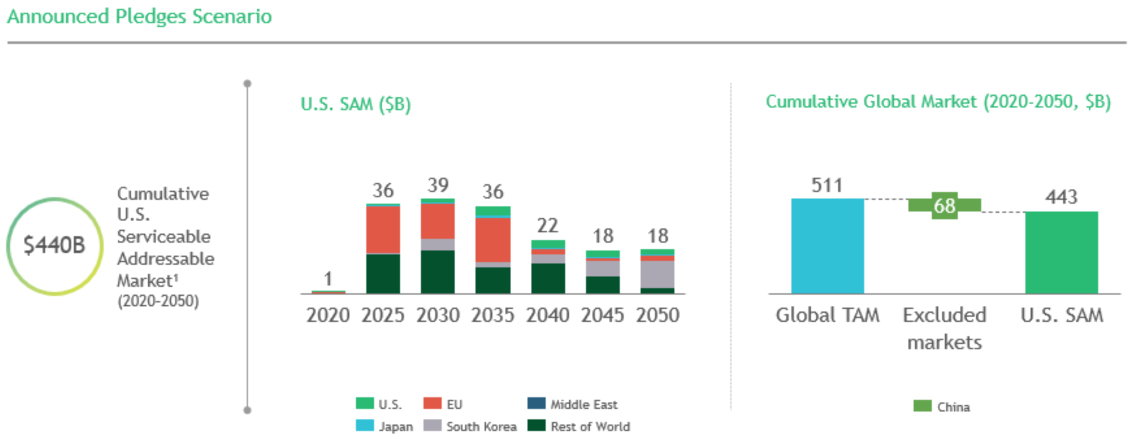


Figure 6.3 - OEM annual market value, Announced Pledges Scenario (APS)

6.3.2 Project Development

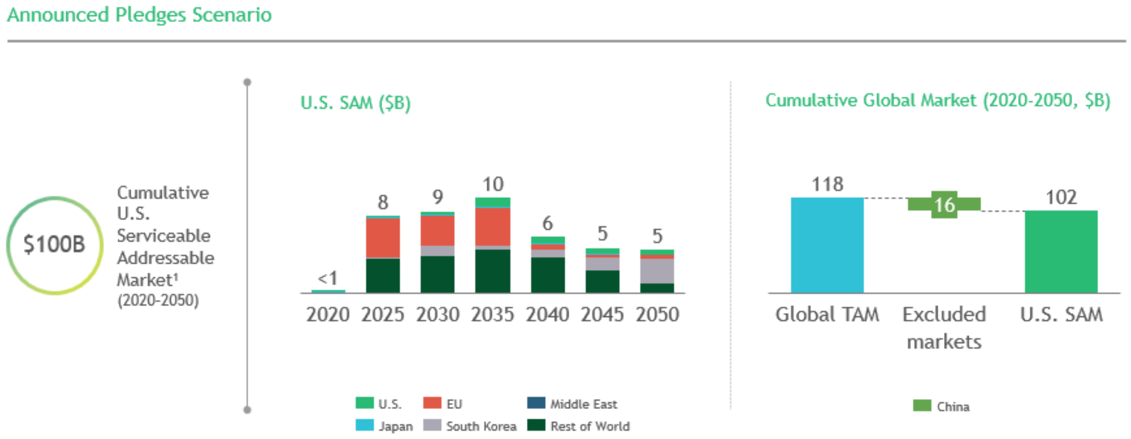


Figure 6.4 - Project Development annual market value, Announced Pledges Scenario (APS)

- U.S. SAM comprises ~85-90% of global TAM, with remaining ~10-15% in inaccessible markets such as China
- The E.U. retains significant value across scenarios, providing additional certainty in export market prioritization
- Peak in ~2030 under NZE reflects necessary project undertakings to meet deep decarbonization goals

6.3.3 Transport and Storage

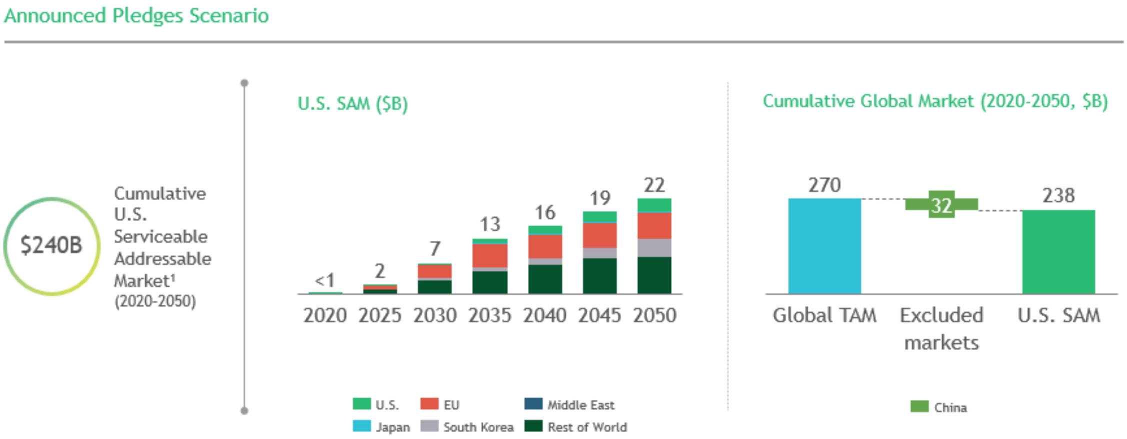


Figure 6.5 - Transport and Storage annual market value, Announced Pledges Scenario (APS)

- Under all scenarios, the need for transportation and storage grows with overall hydrogen demand; this segment is a crucial lever to facilitating global hydrogen offtake. Export in this segment includes both equipment (e.g., H2 import/export machinery) and technical expertise (e.g., import/export facility and pipeline design, Liquid organic hydrogen carrier (LOHC) technology).
- U.S. SAM comprises ~85-90% of global TAM, with remaining ~10-15% in inaccessible markets such as China
- The E.U., Japan, and South Korean markets retain significant value across scenarios, providing additional certainty in export market prioritization

6.3.4 Offtake

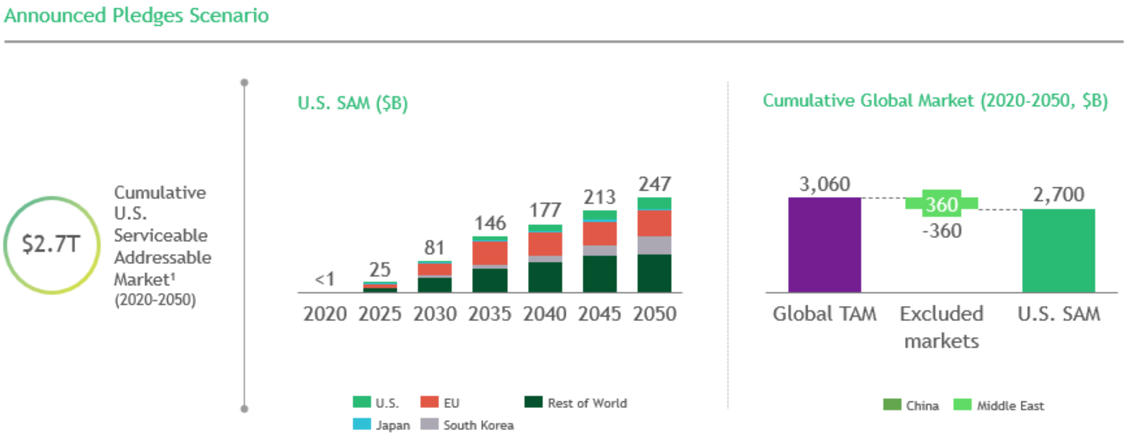
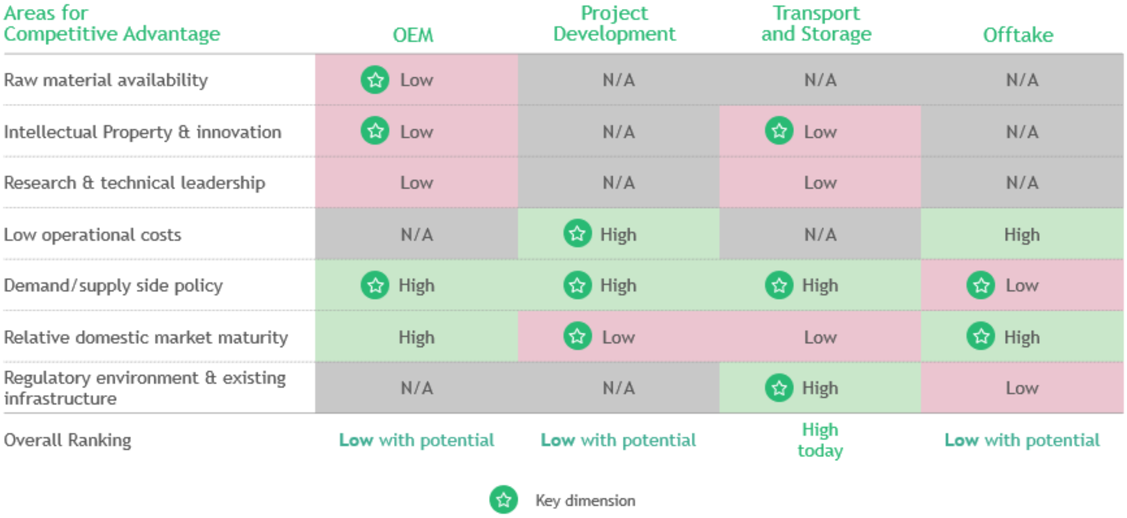


Figure 6.6 - Offtake annual market value, Announced Pledges Scenario (APS)

- Offtake SAM is the largest across all segments, supported by forecasted growth in hydrogen use cases under all scenarios

- U.S. SAM comprises ~80-85% of global TAM, with remaining ~10-15% in inaccessible markets such as Middle East and China
- The E.U., Japan, and South Korean markets retain significant value across scenarios, providing additional certainty in export market prioritization

6.4 Overview of competitiveness



Areas for Competitive Advantage	OEM	Project Development	Transport and Storage	Offtake
Raw material availability	★ Low	N/A	N/A	N/A
Intellectual Property & innovation	★ Low	N/A	★ Low	N/A
Research & technical leadership	Low	N/A	Low	N/A
Low operational costs	N/A	★ High	N/A	High
Demand/supply side policy	★ High	★ High	★ High	★ Low
Relative domestic market maturity	High	★ Low	Low	★ High
Regulatory environment & existing infrastructure	N/A	N/A	★ High	Low
Overall Ranking	**Low** with potential	**Low** with potential	High today	**Low** with potential

★ Key dimension

Figure 6.7 - Current U.S. competitive advantage across key areas, by segment

Figure 6.7 summarizes U.S. competitive advantage across the 4 prioritized segments for low-carbon H_2. Current U.S. competitive advantage is classified as "High" or "Low" (see Figure 3.1 and 10.3 for methodology), with a summary ranking in the final row that is used for plotting in Figure 10.12. Recommendations focus on key dimensions of competitive advantage, denoted by the green star, because these dimensions must be unlocked to create durable competitive advantage. Explanations of competitive advantage ranking and key dimensions by value chain segment can be found in the main text.

- Raw material availability (Low): Raw materials are critical inputs for low-carbon H_2 OEM, especially for electrolysers, which are made using geographically constrained metals (e.g., Pt, Co, Ir, Gd, Ce, Zr). China and South Africa currently control over 90% of mining for these raw materials.

- Intellectual property & innovation (Low): Innovation in OEM and transport & storage enables decreased costs and increased scale of low-carbon H_2 production. Development of innovative H_2 OEM (e.g., electrolysers and reformers) is exportable and enables the entire H_2 value chain. Novel IP for transport & storage methods (e.g., LOHC and ammonia cracking) can dramatically reduce H_2 production costs, leading to increased H_2 demand. Current leaders in patent volume for H_2 OEM (e.g., electrolysers and reformers) are China (> 3x U.S. patent volume), Japan, and South Korea, while patents for H_2 transport and storage are led by Europe (EU at 4x U.S. patent volume), Japan, and China.

- Low operational costs (High): Energy inputs are the largest operational expense for low-carbon H_2 production. Affordable and abundant renewable energy is needed for cost-effective green H_2 production. The U.S. is well-positioned to develop and operate H_2 facilities at lower relative costs with its significant solar and wind resources.

- Demand / supply side policy (Varies by segment): Reduced production costs and guaranteed H_2 offtake create robust H_2 demand that de-risks commercial-scale H_2 development. Largescale H_2 production and export also requires increased supply of transport and storage infrastructure. Policies can be used to address these demand and supply needs. The U.S. has strong policies targeting reduction of H_2 production costs (i.e., DOE H_2 Shot and IIJA funding for clean H_2 electrolysis). The U.S. is a clear leader in H_2 transport & storage investment (e.g., IIJA Regional Clean H_2 Hubs, DOE HyBlend initiative), along with Germany and Japan. However, the U.S. lags the EU by not having H_2 procurement targets, which are critical for establishing offtake demand.

- Domestic market maturity (Mixed): A history of previous low-carbon H_2 projects encourages private investments by demonstrating previous success and reduces project costs through increased facility efficiencies. Maturity of H_2 use cases guarantees robust demand, which de-risks scaling H_2 production. Currently, the U.S. is significantly behind on green H_2 project development (42x fewer projects than EU), though it leads in active blue H_2 projects (> 9x production in EU). As one of the world's largest consumers of H_2 today (~13% global demand), domestic offtake potential to support a rapidly growing U.S. low carbon H_2 market is high.

- Existing Infrastructure (High): Geological storage and pipeline access for transport & storage in H_2 production are critical enablers for project development and end use of H_2, which enables competitive participation across value chain segments. The U.S. has a high competitive advantage with 75% of globally operating hydrogen salt cavern storage sites and >90% of global H_2 pipelines are in the EU and U.S.

6.5 Summary of findings

Low carbon H_2 deployment at scale in the U.S. faces challenges technology-wide and relevant to each prioritized value chain segment. Both the development of potential domestic market and export competitiveness for U.S. low carbon H_2 producers are limited by these challenges. To scale low carbon H_2 and enable offtake export, the U.S. must develop a robust domestic market that allows players to achieve cost reductions through learnings and economies of scale.

Technology-Wide (**including Offtake**) The U.S. is well positioned to maintain and develop competitive advantages for low-carbon H_2, both along the value chain and for the final offtake of H_2 molecules and derivates (e.g., ammonia). The U.S. has technology, infrastructure, and skilled labor from synergistic industries (e.g., oil and gas) and affordable renewable energy potential. The U.S. is a major player in low-carbon H_2 with strong investments in critical infrastructure and electrolyser technology, and aggressive H_2 consumption goals. To maintain competitiveness with other leaders (e.g., Germany, China, and Japan), the U.S. must strategically invest, enact policy, and work with main export partners.

Challenge A: There is a risk that countries with aggressive net-zero targets may not accept low-carbon blue H_2 (e.g., the EU defines "clean hydrogen" as renewable hydrogen). Blue H_2 comprises 20-60% of the U.S. H_2 market size through 2050 across the scenarios. However, with additional carbon capture (e.g., DAC for CO_2 emissions not captured in CCUS) and upstream methane emissions mitigation, blue H_2 can reach comparable carbon intensity on an LCA basis to renewable H_2, allowing for use under more aggressive net zero emissions targets. If Blue H_2 with zero emissions on an LCA basis is not included in clean H_2 definitions, the U.S. could lose out on a sizeable opportunity for energy export. A global lo-carbon market can be enabled by universal standards, like those being supported by the EU, Australia, and IPHE[14]. Selection of potential actions:

- Work with main export partners to ensure methane-derived H2 (e.g., steam methane reformation with CCUS (blue), pyrolysis (turquoise) is acceptable for their emissions reduction targets: Country-specific policies related to low- vs. zero-carbon product use and import could restrict U.S. H2 exports. Blue H2 with similar carbon footprint to green H2 on an LCA basis, should be agreed upon with foreign trading partners as acceptable under their net-zero targets. Example levers may include:
- Encourage development of standards (e.g., carbon intensity requirements on an LCA basis) and regulations (e.g., H2 taxonomy, certificate of origin) for low- and zero-carbon H2, foster alignment on definitions with key import regions

Challenge B: Low carbon H_2 demand is currently limited, largely due to high H_2 production costs and limited proven use cases. Robust, secure demand is needed to encourage investment in innovation and commercial scale deployment for low-carbon H_2. Beyond currently limited uptake, H_2 demand is constrained by high H_2 production costs, including both capital for facility creation and operating expenses. Selection of potential actions:

- Support development of robust H2 offtake demand: Increased H2 demand can de-risk investment in innovation (e.g., for electrolysers) and H2 development at scale which drive cost reductions. Example levers may include:
    - Establish government procurement targets and agreements for end uses of H2 to create reliable demand
    - Encourage uptake of H2 and H2 derivatives (e.g., zero-carbon fuel standard, industry-specific abatement costs)
    - Support domestic H2 production: Reducing the currently high costs of H2 production would increase H2 cost competitiveness and increase demand. Example levers may include:
    - Support cost reduction for H2 production (e.g., financial incentives like tax credits or grants)

Challenge C: Green premium for renewable H_2 production, which is still a factor in most locations, can hinder scaled deployment. Green H_2 is 3-4x more expensive than grey (and 1.5-2x more expensive than blue H_2) in the U.S. and EU, according to BCG cost models. Green H_2 requires co-location with RE or expansion of the low-carbon grid, which poses the challenge of attracting investors to finance high CapEx/OpEx costs for new technology. However, in locations with low RE costs, green H_2 could more quickly achieve cost-competitiveness with fossil-based hydrogen[15]. Selection of potential actions:

- Support scaling of affordable clean energy: Low renewable energy costs are critical to enable cost competitiveness of domestic green H2 vs. current grey H2 processes. Domestic green H2 production can be accelerated by faster development of RE facilities,

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[14] Australian Government, Department of Industry, Science, and Resources; CertifHy

[15] Making the Breakthrough: Green Hydrogen Policies and Technology Costs

including permitting and approvals. Minimal transmission of energy from co-located RE facilities can further increase green H2 cost-efficiency. Example levers may include:
    - Support accelerated project development for co-located energy facilities (e.g., streamlining permitting)
    - Continue to incentivize renewable energy facility development (e.g., tax credits)

OEM: The U.S. advantage in OEM for low-carbon H_2 stems from innovative IP, impactful research, and globally leading private investments in electrolysers. However, established players in the EU and low-cost electrolysers from China pose strong competition in the low-carbon H_2 market. Emerging technologies for electrolysers could lower the costs for more reliable electrolysers in the EU and U.S., but are relatively immature. For blue H_2, the U.S. is the clear global leader, with investments over 8x that of China, in second place.

Challenge D: Geographically-limited access to critical raw materials and clear dominance in the market by players from China and the EU create significant hurdles for the U.S. to develop competitive advantage in electrolyser OEM today. With China's dominance of cost-competitive electrolysers, there is concern about the possible dependency on China for a critical component for low carbon H_2 production. Selection of potential actions:

- Support innovation of electrolysers and reformers: Innovative electrolysers for green H2 that do not require rare metals could decrease electrolyser production costs, allowing the U.S. to compete with low-cost Chinese electrolysers and decreasing green H2 production costs, both of which could increase U.S. H2 demand. For blue H2 reformers, innovation is needed to increase energy efficiency and efficacy, which would decrease operating costs. Example levers may include:
    - Support innovation for novel electrolyser technologies (e.g., DOE research and H2 shot funding) and improvements for reformers and catalytic hydrogen production
    - Encourage research collaboration among national labs, universities, and the private sector (e.g., grant opportunities)

Project Development: The U.S. has an opportunity to increase its competitive advantage in domestic project development to support production of H_2 and H_2 derivatives. To do so, it should take advantage of its synergistic experience in the oil and gas industry, affordable renewable energy potential, access to relatively low-cost natural gas, and abundant sequestration sites. The U.S. also has a strong opportunity to export project development services for deploying industrial-scale low-carbon H_2 projects to countries without experience, especially in the short term.

Challenge E: Financial risks for development of commercial scale facilities for more nascent low carbon H_2 production discourage the scale of project development necessary to achieve economies of scale and increase learnings, both of which will lead to decreased costs of H_2. Both essential infrastructure and reasonable processes for securing permissions to bring a facility online (e.g., permits for CO_2 sequestration for blue H_2 projects) can enable H_2 project development. Creation of H_2 commercial-scale facilities is expensive and developers risk not recovering their investment, especially if storage permitting is delayed. Increased H_2 supply from accelerated deployment is necessary to support a growing H_2 market. Selection of potential actions:

- Continue supporting centralized project development and funding: Centralized projects (e.g., H_2 hubs) de-risk development by reducing capital and operating costs. This enables faster scaling of H2 production, which will further reduce costs and increase H2 demand. Example levers may include:

  - Support development of centralized infrastructure (e.g., DOE H2 hubs funded in IIJA) that provides critical components for H2 project development, including permitting, energy access, pipelines, and CO2 injection capability
  - De-risk nascent industrial-scale H2 projects by OEMs and developers (e.g., low-cost development financing or cost-sharing agreements)
  - Encourage piloting industrial-scale electrolyser technology, which can generate both cost savings and defendable IP via system design and optimization

- Foster accelerated review and approvals processes: Construction of large H_2 facilities will require approvals and permitting for zoning, safety, and environmental impact. Example levers may include:
  - Support prioritized/accelerated review of H_2 projects to enable faster scaling of H_2 production
- Transport and Storage: The U.S. has a strong advantage in transport and storage due to existing H_2 pipeline and export infrastructure, abundant storage potential, and leading transport and storage innovation. Relevant industry experience and extensive oil and gas pipeline infrastructure that could be repurposed round out the U.S. competitive advantage in connecting H_2 production to end uses or export facilities.

Challenge F: Currently limited and expensive H_2 infrastructure restricts U.S. export potential and domestic utilization of H_2, thus limiting the ability to capture market value for low carbon H_2. High costs and limited supply for transport and storage of H_2 also contribute to higher production costs. To increase demand, it is critical to expand infrastructure and decrease costs for transport and storage. Selection of potential actions:

- Enable repurposing natural gas infrastructure for H2 domestically and with export partners. Retrofitting natural gas pipelines can be cheaper than creating new H2 pipelines. For retrofits, owners of existing pipelines must be willing to have them converted for H2 use. Example levers may include:
  - Encourage companies to repurpose their existing infrastructure for H_2, where feasible and affordable (e.g., tax credits, grants)
- Support innovation of H_2 transport and storage: Innovative technologies, like liquid organic hydrogen carriers (LOHC) and ammonia cracking, have significant cost-reduction potential for H_2 transport and storage. Example levers may include:
  - Continue to support research and innovation for novel H_2 transport technologies (e.g., DoE grants)

7 Electrochemical Long Duration Energy Storage

Electrochemical long duration energy storage (LDES) is a nascent set of technologies which enables high penetration of intermittent renewable resources by providing multiday and intra-season storage for renewable production. LDES specializes in providing storage with discharge durations of >8 hours, while Li-ion batteries are economically limited to 8-12 hours, limiting use cases. Unlike Li-ion, LDES can decouple power and energy, enabling economic storage for much longer durations.[16]

Multiple LDES technologies (such as aqueous electrolyte flow batteries, hybrid flow batteries, and metal air batteries) provide similar services and use cases, which can range from firming intermittent renewables to supporting remote microgrids for communities, industrial users, or military bases. Non-electrochemical LDES options also exist but were excluded from this analysis due to geological limitations (mechanical), lower potential for IP (thermal), or because they are covered elsewhere in the study (chemical, through hydrogen).

7.1 Overview of LDES value chain segments

The electrochemical LDES value chain, detailed further in appendix slide 48, is shown below. Offtake, marked in Figure 7.1 below as a key enabler (e.g., an important enabler for competitiveness but not a key segment for commercial focus) and was thus not included for detailed market sizing but was addressed in the recommendation sections below.

In assessing areas for additional analyses, the study focused on two areas:

- **OEM,** the segment where LDES battery packs and sub-components are produced, is a key area of focus due to the large market potential and the ability to build and maintain competitive advantage through IP and advanced manufacturing economies of scale
    - While **O&M** includes both the sophisticated battery management system (BMS) software and the physical maintenance activities, the operations software component of O&M presents an opportunity for U.S. players to build an IP-based advantage

- **Raw materials** were not prioritized, because most materials (except for vanadium) are widely available at low cost in global commodity markets, and there is little opportunity for competitive advantage. **Project development,** meanwhile, is expected to shift to a model similar to Li-ion, where standalone developers integrate OEM-provided technologies into projects. **Financing** is challenging for LDES projects, with few avenues to build competitive advantage. **EPC**, **transport and storage,** and **offtake** were also deprioritized for being largely local with little export opportunity.

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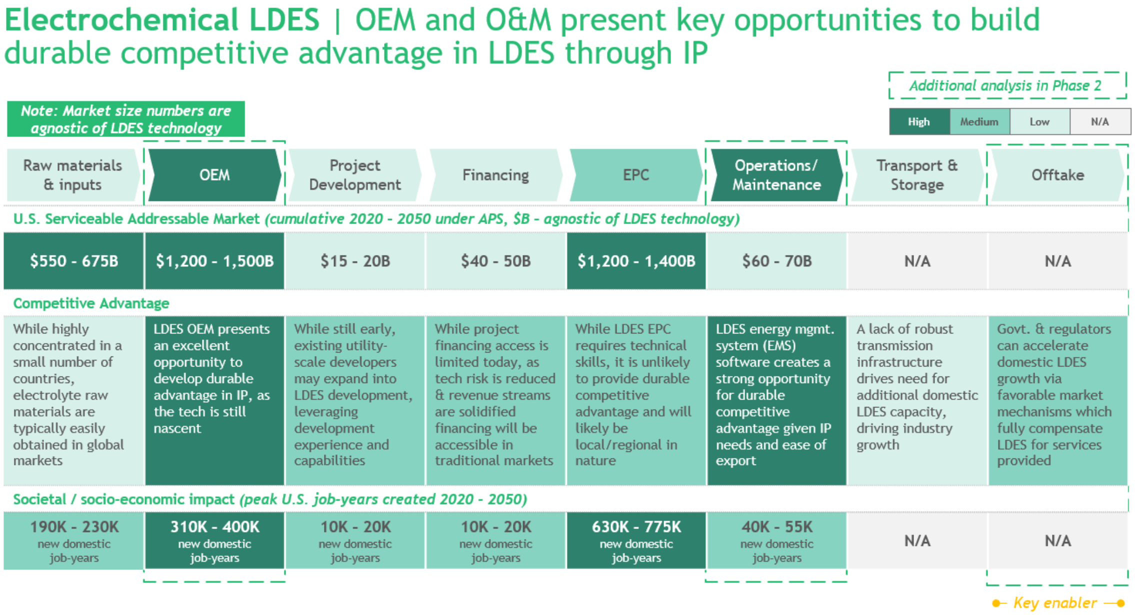
[16] New LDES Council Report Finds Up to 140 TWh of Long-Duration Energy Storage Needed to Enable Grid Net Zero by 2040 at Lowest Cost



Electrochemical LDES | OEM and O&M present key opportunities to build durable competitive advantage in LDES through IP

Note: Market size numbers are agnostic of LDES technology

Additional analysis in Phase 2

High | Medium | Low | N/A

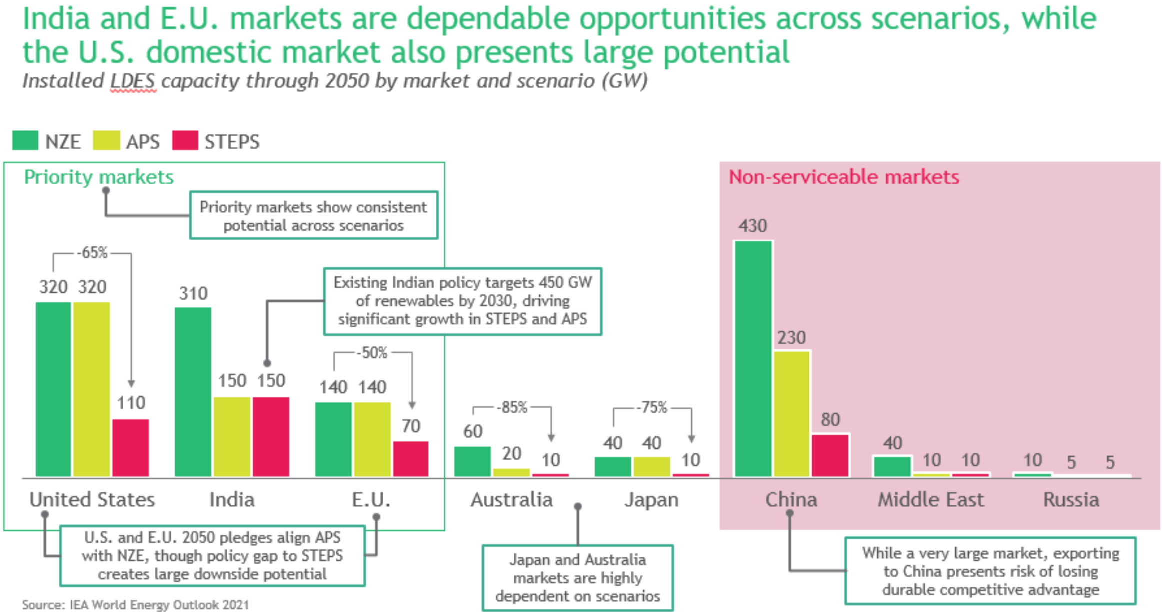
	Raw materials & inputs	OEM	Project Development	Financing	EPC	Operations/ Maintenance	Transport & Storage	Offtake
U.S. Serviceable Addressable Market *(cumulative 2020 - 2050 under APS, $B - agnostic of LDES technology)*	$550 - 675B	$1,200 - 1,500B	$15 - 20B	$40 - 50B	$1,200 - 1,400B	$60 - 70B	N/A	N/A
Competitive Advantage	While highly concentrated in a small number of countries, electrolyte raw materials are typically easily obtained in global markets	LDES OEM presents an excellent opportunity to develop durable advantage in IP, as the tech is still nascent	While still early, existing utility-scale developers may expand into LDES development, leveraging development experience and capabilities	While project financing access is limited today, as tech risk is reduced & revenue streams are solidified financing will be accessible in traditional markets	While LDES EPC requires technical skills, it is unlikely to provide durable competitive advantage and will likely be local/regional in nature	LDES energy mgmt. system (EMS) software creates a strong opportunity for durable competitive advantage given IP needs and ease of export	A lack of robust transmission infrastructure drives need for additional domestic LDES capacity, driving industry growth	Govt. & regulators can accelerate domestic LDES growth via favorable market mechanisms which fully compensate LDES for services provided
Societal / socio-economic impact *(peak U.S. job-years created 2020 - 2050)*	190K - 230K new domestic job-years	310K - 400K new domestic job-years	10K - 20K new domestic job-years	10K - 20K new domestic job-years	630K - 775K new domestic job-years	40K - 55K new domestic job-years	N/A	N/A

Key enabler

Figure 7.1 – Electrochemical LDES Value Chain Prioritization Results

7.2 Size of the opportunity in domestic market and exports

The U.S., India, and EU markets are expected to be the largest serviceable markets for U.S.-based LDES players. See Table 3.1 for more detailed market selection information.



India and E.U. markets are dependable opportunities across scenarios, while the U.S. domestic market also presents large potential

Installed LDES capacity through 2050 by market and scenario (GW)

Priority markets show consistent potential across scenarios

Existing Indian policy targets 450 GW of renewables by 2030, driving significant growth in STEPS and APS

U.S. and E.U. 2050 pledges align APS with NZE, though policy gap to STEPS creates large downside potential

Japan and Australia markets are highly dependent on scenarios

While a very large market, exporting to China presents risk of losing durable competitive advantage

Source: IEA World Energy Outlook 2021

Figure 7.2 – Electrochemical LDES Cumulative Deployment Potential by Priority Market

The total U.S. Serviceable Addressable Market (SAM) for electrochemical LDES battery packs is estimated to be 800 – 1,000 GW under the APS scenario, ranging from ~500 GW under STEPS to ~2,200 GW under NZE. The size of the market is $1.3 – 1.5T under APS ($0.7T STEPS - $3.5T NZE).

Figure 7.3 – U.S. Serviceable Addressable Market by Value Chain Segment

The U.S. SAM is expected to be led by the domestic market of ~320 GW under APS (~100 GW STEPS – 320 GW NZE) GW or $0.5T ($0.2T STEPS – $0.5T NZE), followed by India at ~150 GW APS (150 STEPS – 310 GW NZE) GW or $0.2T ($0.2T STEPS – $0.5T NZE). The EU comes in at a close third, with ~140 GW APS (70 GW STEPS - 140 GW NZE) or $0.2T ($0.1T STEPS – $0.2T NZE).

The U.S. Serviceable Obtainable Market (SOM), which reflects the portion of the global market which U.S.-based companies could realistically capture, is estimated to be 10 – 50% of the global market based on precedents set by the Li-ion industry. The lower bound of the range is based on the current estimated U.S. share of global Li-ion manufacturing capacity while the upper bound is based on the global leader in Li-ion manufacturing capacity, currently China.[17] This range reflects the spread of market share which the U.S. could potentially capture, with the lower bound (~10%) reflecting business as usual without strategic support while the upper bound (~50%) reflects what a market leader could capture. U.S.-based players, particularly in the OEM space, can achieve market share closer to the upper bound by building a competitive moat through early leadership in technology quality, by capturing economies of scale in manufacturing, and developing expertise and IP in relevant advanced manufacturing processes.

Several markets were considered non-addressable for the U.S. in this study, including China, Russia, and the Middle East. China was excluded due to IP concerns related to forced technology transfers and lax IP protections, as well as the presence of state-backed domestic players. Russia and the Middle East were excluded as storage and resource adequacy needs are more likely to be met by fossil fuel plants with CCUS or with blue hydrogen. Of these, China is by far the largest potential market, with ~230 GW under APS through 2050 (80 STEPS - 430 GW NZE).

Priority Markets	Relevant Drivers for Market Deep Dive
European Union	• Single trading bloc with friendly U.S. relations • Large expected market for energy storage supported by announced net zero pledges and large renewable potential • Efforts to wean off of Russian gas may require additional firming capability for intermittent renewables

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[17] Global Battery Arms Race: 200 Gigafactories; China Leads

	• Established power markets enable long-term financing
India	• Large economy with significant growth potential in the power sector to support development • Ambitious policy targets in place to expand renewable generation, targeting 450 GW of renewables by 2030 • Fragmented transmission system increases value of storage to address renewable intermittency
Japan	• Large economy with friendly U.S. trade relations with a 2050 carbon neutrality pledge • Recent Green Growth Strategy targets 50-60% renewable penetration, driving need for LDES to ensure resource adequacy • Need for EC-LDES may be offset, however, by significant geothermal potential in Japan and an early focus on hydrogen
Australia	• Large economy with friendly U.S. trade relations and a 2050 carbon neutrality pledge • Significant potential for renewable energy likely to drive need for LDES, particularly considering high costs of building transmission infrastructure across large distances • Note: Recent 2050 carbon neutrality pledge is not reflected in latest dataset underpinning analysis

Excluded Markets	Relevant Drivers for Exclusion
China	• No hard barriers to entry exist today • Significant concerns exist around ceding competitive advantage if forming a JV for LDES production in China, which is the common model seen by other technologies historically • China is focusing on building a domestic vanadium-based LDES industry, given China's significant share of global vanadium resources
Russia	• Near-term market access barriers due to ongoing conflict in Ukraine and related sanctions • Long-term market is viewed as inaccessible to U.S. electrochemical LDES as market is expected to rely more heavily on blue H2 for long duration energy storage needs, given significant gas reserves and production capacity
Middle East	• No hard barriers to entry exist today, aside from sanctioned markets like Iran • Long-term market is viewed as inaccessible to U.S. electrochemical LDES as market is expected to rely more heavily on blue H2 for long duration energy storage needs, given significant gas reserves and production capacity

Table 6.1 – Priority and Inaccessible Markets

7.3 Segment level analysis

7.3.1 OEM

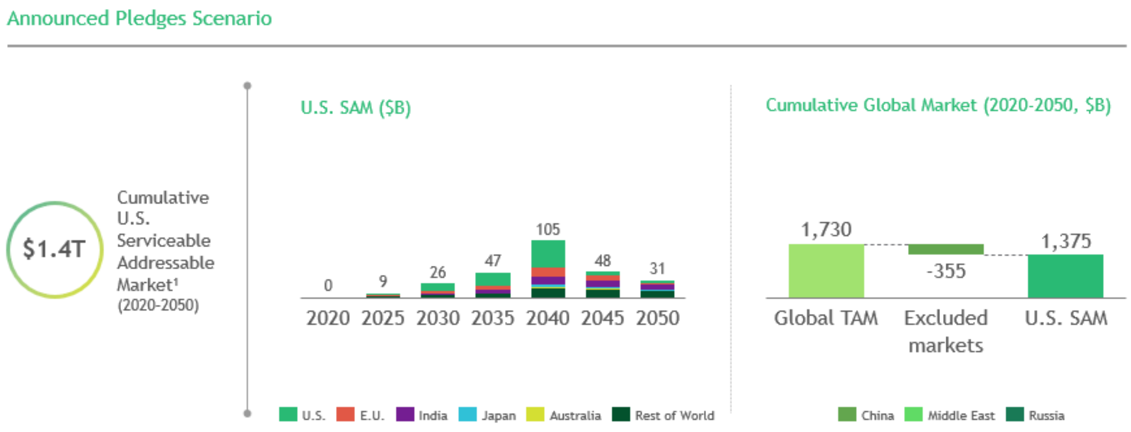


Figure 7.4 – U.S. OEM Serviceable Addressable Market by Year (APS)

- U.S. SAM comprises 80 - 85% of global TAM, with remaining 15 - 20% largely concentrated in the Chinese LDES market
- The U.S. SAM loses 60 - 80% of market value outside of the NZE, with India and the remaining non-targeted markets losing the majority of value
- Across scenarios, the LDES market grows significantly in the 2030s, requiring a large buildout of manufacturing capacity in the coming decade to meet projected demand
- Top three priority markets (U.S., India, and the E.U.) are expected to comprise ~70% of the U.S. SAM in the APS and STEPS scenarios, making early focus on these markets key

7.3.2 O&M Software

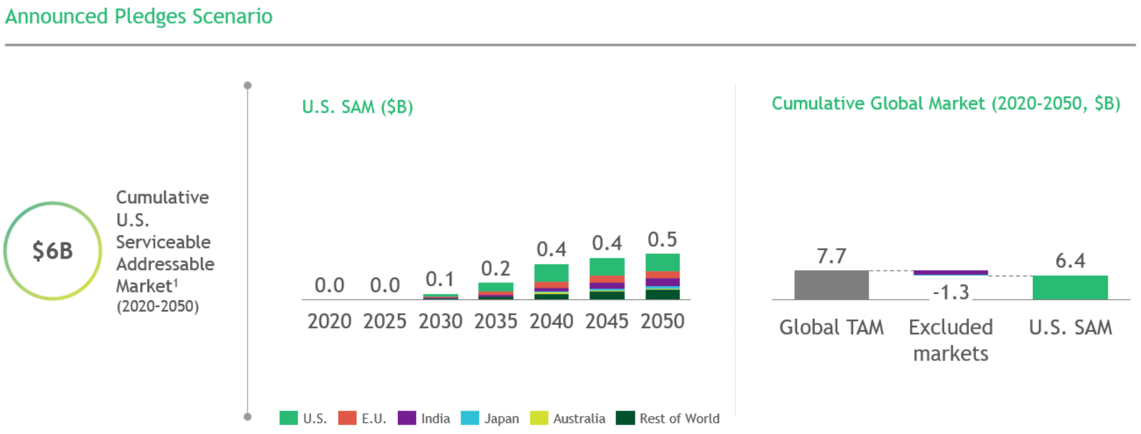
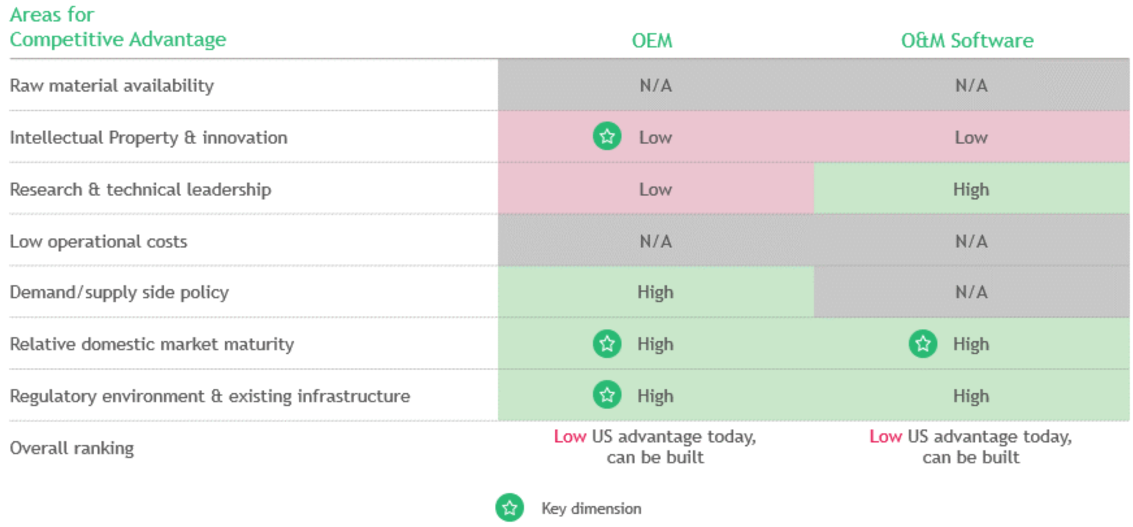


Figure 7.5 – U.S. O&M Software Serviceable Addressable Market by Year (APS)

- Margins for operations software have potential to be quite large, in the range of 60 – 70% based on other software as a service offering
- O&M operations software market is expected to grow steadily over time as more capacity begins to operate, with a large jump in the 2030s
- U.S. SAM comprises 80 - 85% of global TAM, with remaining 15 - 20% largely concentrated in the Chinese LDES market
- Market for storage operations software may be larger due to potential overlap with Li-ion grid-scale storage assets

7.4 Overview of competitiveness

Figure 7.6 below summarizes U.S. competitive advantage across the two prioritized segments, OEM and O&M software. Current U.S. competitive advantage is classified as "High" or "Low" (see Figures 3.1 and 10.3 for methodology), with a summary ranking in the final row that is used for plotting in Figure 10.12. Recommendations focus on key dimensions, denoted by the green star, because these dimensions must be unlocked to create durable competitive advantage. Explanations of competitive advantage ranking and key dimensions by value chain segment are included below.



Areas for Competitive Advantage	OEM	O&M Software
Raw material availability	N/A	N/A
Intellectual Property & innovation	☆ Low	Low
Research & technical leadership	Low	High
Low operational costs	N/A	N/A
Demand/supply side policy	High	N/A
Relative domestic market maturity	☆ High	☆ High
Regulatory environment & existing infrastructure	☆ High	High
Overall ranking	Low US advantage today, can be built	Low US advantage today, can be built

☆ Key dimension

Figure 7.6 – U.S. Current Competitive Advantage by Segment

Key LDES competitiveness findings include:

- Raw Material Availability (N/A): Most of the leading electrochemical LDES technologies (e.g., iron-air, hybrid flow batteries) are primarily based on widely available inputs

- Intellectual Property & Innovation (Low): Relevant for OEM, the U.S. ranks 4th globally in patent volume in both flow batteries and metal air batteries. U.S. patent volumes are significantly behind China and South Korea which filed ~2-3x the volume of LDES patents since 2015, while also slightly trailing Japan. U.S., South Korean, and Japanese patent leaders tend to be OEM or advanced manufacturing players (e.g., ESS, Sumitomo, LG Chem, Lotte Chemical), while Chinese patents are driven by research institutions (Chinese Academy of Sciences)

- Relative Domestic Market Maturity (High): U.S. OEM companies maintain a significant lead in investment, with investments in U.S.-based companies ~6x that of companies based in China, the market with the second-highest investment in domestic companies

- Regulatory Environment & Existing Infrastructure (High): The U.S. transmission grid creates opportunity for LDES to close transmission gaps to enable high renewable penetration, giving U.S. players an early potential market to begin building a competitive moat. However, a mixed set of power market regulations across the U.S. drive varying degrees of LDES potential, though overall the ecosystem creates opportunity to invest in and finance storage projects

7.5 Summary of findings

The U.S. holds a near-term advantage in LDES due to a more mature market and ecosystem compared to other countries, with domestic players attracting significant private investment. This early lead, however, may be limited if challenges related to uncertain demand and high costs are not addressed. Further, the opportunity to build an early-mover advantage may be lost if gaps in patents and research are not closed, particularly in manufacturing. These key challenges and potential solutions are expanded upon below. If left unaddressed, the challenges limit both a potential domestic market and the export competitiveness for U.S. players. These two concepts are intertwined, as a robust domestic market gives U.S. players the opportunity to perfect nascent LDES products and develop cost advantages through learnings and economies of scale.

Note that, while the analysis below has largely been focused on electrochemical LDES, the technology-wide recommendations below would apply to all LDES options (such as thermal, mechanical, or chemical technologies).

Challenge A: Electrochemical LDES is a nascent technology with uncertain demand. Both the LDES market and technology are still developing, limiting near-term growth potential. The need for LDES, spurred by high renewable penetration, is limited today and may be pushed further into the future if other solutions – such as transmission expansion or advanced nuclear - gain ground. Further, Li-ion is currently more cost competitive for durations up to ~12 hrs and there is little need for longer duration storage until renewable penetration increases further. Selection of potential actions:

- Drive a robust pipeline of technology-agnostic LDES demand: Increased demand for LDES projects builds domestic advantage by enabling cost reductions through de-risked private investment in manufacturing and R&D, economies of scale, and learnings from repeated deployment. Example levers may include:
    - Strengthen net-zero targets and requirements for zero-carbon energy (e.g., 24/7 carbon free energy requirements)
    - Set targets for long duration energy storage services (e.g., state procurement mandates)
- Ensure LDES services can be accurately modeled and compensated: Reformed power market policies can improve LDES project economics and competitiveness, indirectly driving up demand and enabling cost reductions through de-risked private investment in manufacturing and R&D, economies of scale, and learnings from repeated deployment. Example levers may include:

    - Implement new mechanisms to fully compensate LDES for the range of potential services rendered (e.g., via regulated rate-based cost recovery, updated capacity accreditation, new market compensation mechanics)
    - Promote research and use of updated grid modeling tools which can accurately evaluate LDES resource performance

Challenge B: High technology costs limit near-term deployment. To be deployed widely, LDES technologies must achieve cost competitiveness relative to other sources of firm generation. Recent studies estimate that LDES technologies may not reach this cost parity until roughly 2030, limiting the near-term potential for U.S. players to build competitive advantage.[18,19] Selection of potential actions:

- Build domestic manufacturing economies of scale: Early investment in advanced domestic manufacturing capacity can drive advantage both through cost reductions from economies of scale and by building a moat around advanced industrial expertise and processes. Example levers may include:
    - Incentivize domestic production of LDES components (e.g., domestic content requirements, tax credits, procurement targets)
    - Expand financing access for domestic LDES manufacturing facilities (e.g., loan guarantees, cost-sharing, tax credit programs)

Challenge C: The U.S. lags in LDES Intellectual Property generation and R&D. As referenced in the "Overview of LDES Competitiveness" section above, the U.S. significantly lags both China and South Korea and slightly lags Japan in terms of total LDES-related patents. Building durable competitive advantage will require the U.S., currently 4th globally in research volume, to maintain pace with patenting leaders. Selection of potential actions:

- Achieve U.S. leadership in LDES innovation: Continued innovation will help the U.S. close the initial gap in IP creation and R&D, building advantage through superior technology quality and innovative cost reductions. Example levers may include:
    - Further facilitate research collaboration among National Labs, universities, and the private sector
    - De-risk technology demonstrations and increasing impact by crafting programs based on achieving commercialization milestones (e.g., increasing access to low-cost financing or cost-sharing programs)

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[18] The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems

[19] New LDES Council Report Finds Up to 140 TWh of Long-Duration Energy Storage Needed to Enable Grid Net Zero by 2040 at Lowest Cost

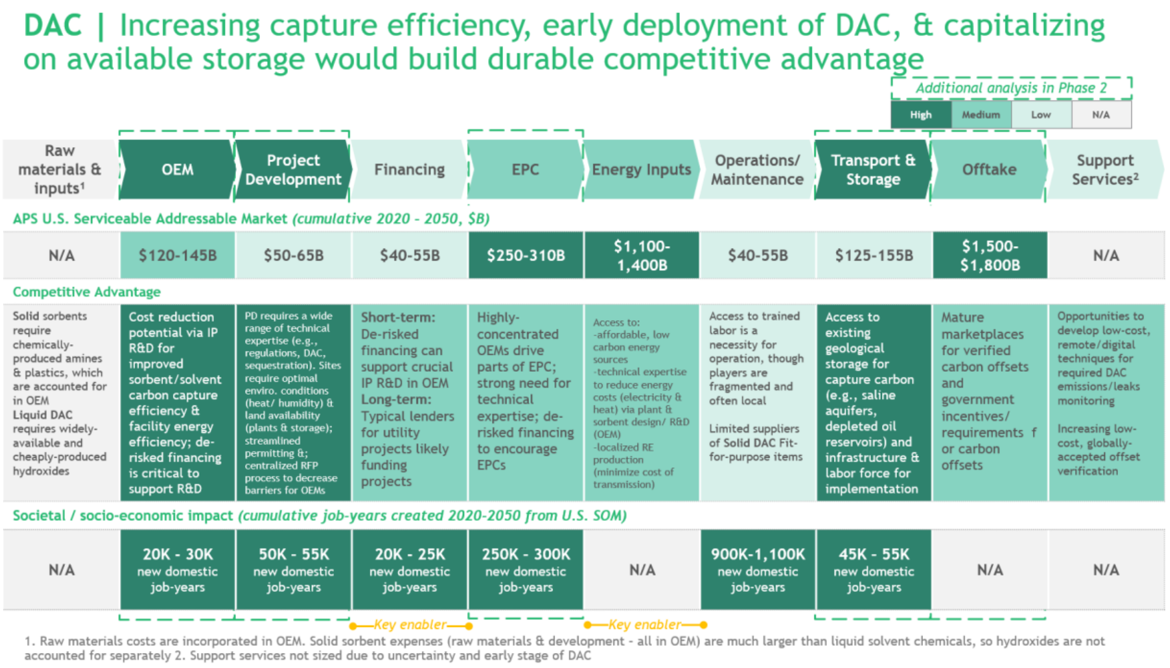
8 Direct Air Capture

Direct Air Capture (DAC) is the capture of carbon from the atmosphere, and represents a uniquely quantifiable, high-quality negative emissions technology. During DAC sequestration, the amount of CO_2 injected for geologic sequestration is measured, effectively removing quantified CO_2 from the atmosphere and creating a "negative emission." Geologic sequestration is considered high permanence, in that greater than 80% of captured CO_2 is effectively removed from the atmosphere for 10,000 years[20].

Reducing carbon emissions across all sectors is important for meeting climate goals, but some hard-to-abate sectors, comprising ~22% of global CO_2 emissions[21], are expected to remain emissions sources, regardless of progressive or limited decarbonization efforts. DAC then can play an important role in decreasing net emissions while decarbonization accelerates. Further, achieving climate goals and limiting future warming will require negative emissions technology, like DAC, to remove historical CO_2 emissions from the atmosphere.

Carbon capture for DAC is conducted using a variety of technologies. Both liquid and solid sorbent technologies are commercially viable and are transitioning to industrial scale. Next-generation technologies like electrochemical and passive carbonization for carbon capture are currently at lab or pilot scale but could increase in prominence due to the dramatic potential energy efficiency they offer compared with liquid and solid DAC. A detailed view of the DAC value chain analyzed in this study is included on appendix page 135.

8.1 Overview of value chain segments considered for this study



DAC | Increasing capture efficiency, early deployment of DAC, & capitalizing on available storage would build durable competitive advantage

Additional analysis in Phase 2

High | Medium | Low | N/A

Raw materials & inputs[1]	OEM	Project Development	Financing	EPC	Energy Inputs	Operations/ Maintenance	Transport & Storage	Offtake	Support Services[2]
APS U.S. Serviceable Addressable Market *(cumulative 2020 - 2050, $B)*									
N/A	$120-145B	$50-65B	$40-55B	$250-310B	$1,100-1,400B	$40-55B	$125-155B	$1,500-$1,800B	N/A
Competitive Advantage									
Solid sorbents require chemically-produced amines & plastics, which are accounted for in OEM Liquid DAC requires widely-available and cheaply-produced hydroxides	Cost reduction potential via IP R&D for improved sorbent/solvent carbon capture efficiency & facility energy efficiency; de-risked financing is critical to support R&D	PD requires a wide range of technical expertise (e.g., regulations, DAC, sequestration). Sites require optimal enviro. conditions (heat/ humidity) & land availability (plants & storage); streamlined permitting &; centralized RFP process to decrease barriers for OEMs	Short-term: De-risked financing can support crucial IP R&D in OEM Long-term: Typical lenders for utility projects likely funding projects	Highly-concentrated OEMs drive parts of EPC; strong need for technical expertise; de-risked financing to encourage EPCs	Access to: -affordable, low carbon energy sources -technical expertise to reduce energy costs (electricity & heat) via plant & sorbent design/ R&D (OEM) -localized RE production (minimize cost of transmission)	Access to trained labor is a necessity for operation, though players are fragmented and often local Limited suppliers of Solid DAC Fit-for-purpose items	Access to existing geological storage for capture carbon (e.g., saline aquifers, depleted oil reservoirs) and infrastructure & labor force for implementation	Mature marketplaces for verified carbon offsets and government incentives/ requirements f or carbon offsets	Opportunities to develop low-cost, remote/digital techniques for required DAC emissions/leaks monitoring Increasing low-cost, globally-accepted offset verification
Societal / socio-economic impact *(cumulative job-years created 2020-2050 from U.S. SOM)*									
N/A	20K - 30K new domestic job-years	50K - 55K new domestic job-years	20K - 25K new domestic job-years	250K - 300K new domestic job-years	N/A	900K-1,100K new domestic job-years	45K - 55K new domestic job-years	N/A	N/A

1. Raw materials costs are incorporated in OEM. Solid sorbent expenses (raw materials & development - all in OEM) are much larger than liquid solvent chemicals, so hydroxides are not accounted for separately 2. Support services not sized due to uncertainty and early stage of DAC

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[20] Estimating geological CO2 storage security to deliver on climate mitigation

[21] Physical and Policy Pathways to Net-Zero Emissions Industry

Figure 8.1 - Direct Air Capture Value Chain Prioritization Results

This study prioritized the **OEM** segment, which includes manufacturing and designing, especially solid sorbent technology of alkanolamines. **Project development** is also critically important to scaling DAC, as it involves commercial facility development that will help move DAC down the cost curve with experience. But while OEMs and paired project developers may control the highest-value engineering and procurement portion, the construction of a DAC facility is likely to be performed by experienced local and regional **EPCs**, who have a potential for early-mover advantage.

Safe, long-term carbon **transport and storage** enables DAC's greatest revenue generation (negative emissions), so geologic potential and regulatory support, along with synergistic oil and gas expertise, creates a distinct advantage for the U.S. **Offtake**, as an end use for either carbon offset (stored) or CO_2 gas (e.g., synfuels, EOR), will require contracting and mature markets. The dominant offtake expected for DAC is carbon credits, which could be purchased as negative emissions to meet environmental compliance or as voluntary negative emissions of a company's emissions. While carbon credits would be generated domestically via sequestration, their value can be exported. As the largest market portion, where the bulk of the financial benefit from DAC occurs, offtake is critical to capture.

Financing in the long term is likely to follow traditional models, so is not considered an area of competitive advantage. Low-cost renewable energy can create competitive advantage across multiple technologies in this study, so **energy inputs** are considered a key enabler for unlocking the DAC value chain, as opposed to an independently prioritized segment for analysis. **O&M, raw materials**, and **support service** providers are generally fragmented.

8.2 Size of the opportunity in domestic markets and exports

The U.S., EU, and U.K. are expected to be the largest opportunities for U.S.-based DAC players across the NZE and APS scenario, followed by the Middle East market, which is only expected to be sizeable under NZE. In evaluating these market sizes, it is important to note that the bulk of DAC deployment is expected to occur between 2040-2050, so this analysis reflects 10-year cumulative values, unlike the 30-year range for other technologies.

The U.S. Serviceable Addressable Market (SAM) in APS for DAC is expected to be ~3 Gt (NZE ~7Gt annual abatement) of the total DAC capacity by 2050, up from no commercial DAC capacity today. The U.S. SAM market in APS will be dominated by the domestic market of ~ 1.9 Gt annual abatement or ~$1,000B, followed by the E.U. at 1.1 Gt or ~$610B and the U.K. at 0.03 Gt or ~$1.5B. In APS, only countries with current investment in DAC and net-zero-by-2050 policies are included in market sizing, as countries with targets beyond 2050 are expected to be focused on decarbonization efforts.

Using low-carbon H_2 as a proxy for currently nascent DAC industry, the U.S. Serviceable Obtainable (SOM) market is expected to be about 15-30% of the total global market. Low-carbon H_2 requires similar infrastructure and logistics to DAC, both of which will likely rely on industry experience in synergistic industries, like oil and gas. Accordingly, the lower bound for DAC aligned with business-as-usual for the U.S. maintaining the current share of global H_2 production, using 2014-2018 to set the baseline. Market leadership, based on the percentage of global H_2 exports obtained by Canada and Belgium each,[22] was then used to establish the upper

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[22] Hydrogen Exports by Country in 2021

end of the SOM range. SOM relies on aligning with main export partners on quality standards of DAC carbon credits and developing mature carbon markets that enable cross border sales. A potential barrier to building and maintaining market share is securing the ability to export DAC credits. The EU Emissions Trading Scheme, currently the most developed carbon market, does not allow for sale of carbon credits created outside the EU. If the U.S. is unable to support development of a less restrictive carbon market, this could limit its ability to realize the economic benefit of DAC. In contrast, if more countries adopt aggressive net zero targets, this will increase DAC demand and can increase U.S. SOM. The U.S. can also increase its SOM with earlier commercial scale development of DAC to achieve greater cost reductions and outcompete other major DAC players.

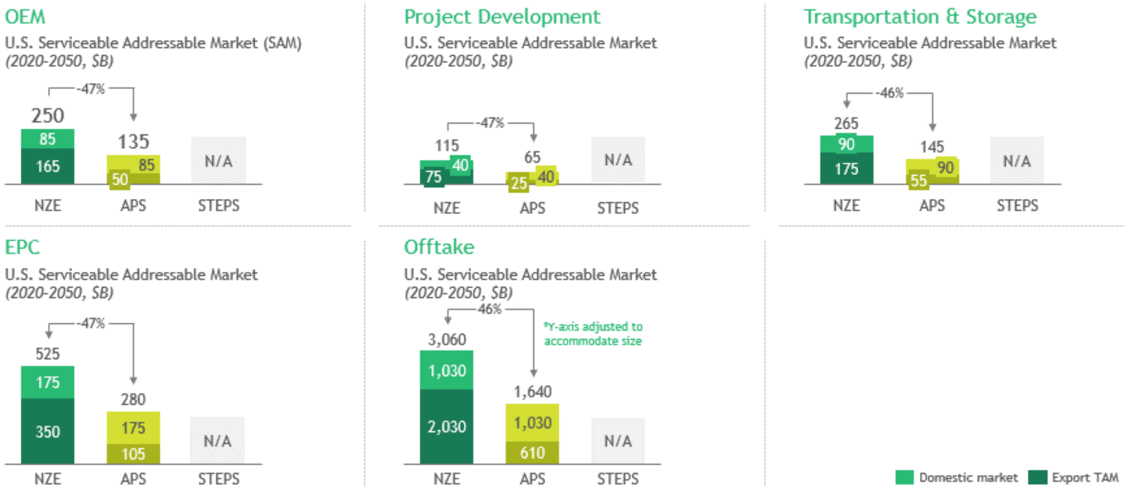

Figure 8.2 - Cumulative Deployment Potential by Priority Market

Priority Markets	Segments included in SAM	Relevant drivers for breakout
EU	• OEM • Project Development • Transport and Storage • Offtake	• There is significant potential for DAC, indicated by the first commercially operating DAC facility launching here, supportive policies and public funding, and a net-zero by 2050 commitment • To meet their aggressive targets, more effective and lower-cost DAC technologies than domestic options (e.g., solid sorbent) are likely to be imported for use in existing/planned facilities • Project development expertise may be imported for this rapidly growing industry, especially if energy or other design efficiencies reached in the U.S. are higher than for domestic project development
U.K.		• Expansion potential for DAC in the U.K. is indicated by strong public funding investment for early-stage DAC technology R&D and in the U.K. commitment of net-zero emissions by 2050 • To reach their aggressive net-zero target, the U.K. is likely to import the most effective and low-cost DAC technology, if it is not produced domestically

		• Project development expertise will be needed to implement at scale any U.K.-funded DAC technology and can be imported from countries that are early movers and have more experience in DAC facility development
Middle East *[NZE}*		• This region has high potential for low DAC costs and, by extension, more cost-competitive offtake. Lower costs for DAC are due to a combination of low fuel prices, high access to storage, high RE potential, and cheaper construction materials • Similarly, to some oil and gas industry in this region, there may be a unique opportunity for the U.S. to export EPC capabilities and labor to areas where abundance of work vs. local availability of engineers is off-balance (e.g., Saudi Arabia, UAE) • Due to a lack of current domestic DAC investments, enabling DAC growth in this region (e.g., OEM technology, project development and transport and storage expertise) will be largely served by imports from other countries, like the U.S.

Inaccessible Markets	**Excluded segments**	**Relevant drivers for exclusion**
China	• OEM • Project Development • Transport and Storage • Offtake	• China's net-zero target is 2070, so it will likely not be a sizeable market for DAC before 2050; the focus is on decarbonization as opposed to negative emissions in this time window • China's domestic investment in CCS is dedicated to CCUS from point sources, a priority that is expected to continue through 2050
Russia		• Russia's net-zero is 2060, so it will likely not be a sizeable market for DAC before 2050 • Russia is more likely to buy DAC capability and/or negative emissions from China instead of the U.S.

Markets to Watch	**Included segments**	**Relevant drivers for future inclusion**
Japan, Canada, Australia	• N/A	• These 3 countries were included as a list of "countries to watch." where net-zero targets by 2050 and government support for DAC R&D make them potential future targets for U.S. exports • Both Canada and Australia have abundant geologic storage, critical for DAC facilities • Carbon Engineering, a major liquid DAC OEM, is headquartered in Canada, though the largest facility planned with its technology will be in the U.S. • Australia has strong potential for affordable renewable energy needed to power DAC

Table 7.1 - Detail on independently modeled countries & regions; *Middle East region only included in SAM for NZE scenario

Under the NZE scenario, U.S. export SAM increases substantially with the inclusion of other countries reaching these ambitious climate goals, including the large Middle East market at ~20% of global DAC by 2050 in NZE[23]. U.S. SAM in NZE becomes export-dominated, with the same domestic and EU market as APS, but with the addition of the Middle East with a market of 1.4 Gt or ~$760B and the "rest of world" minus Russia with ~1 Gt or ~$660B. The low energy costs, abundant geologic storage, and imbalance of available engineers versus required labor make the Middle East a relatively lucrative market for U.S. exports of skilled labor and technology. Both Russia and China were excluded from U.S. SAM projections.

8.3 Segment level analysis

8.3.1 OEM and Project Development

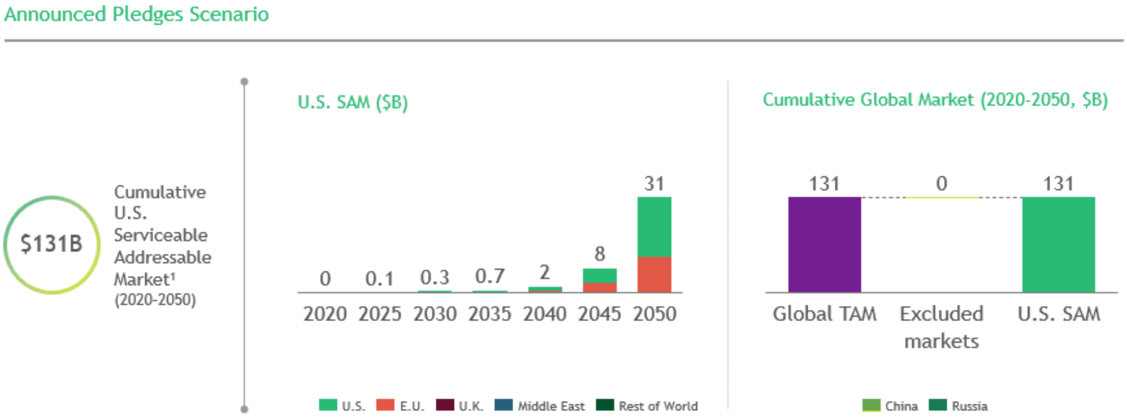

Figure 8.3 - OEM annual market value, Announced Pledges Scenario (APS)

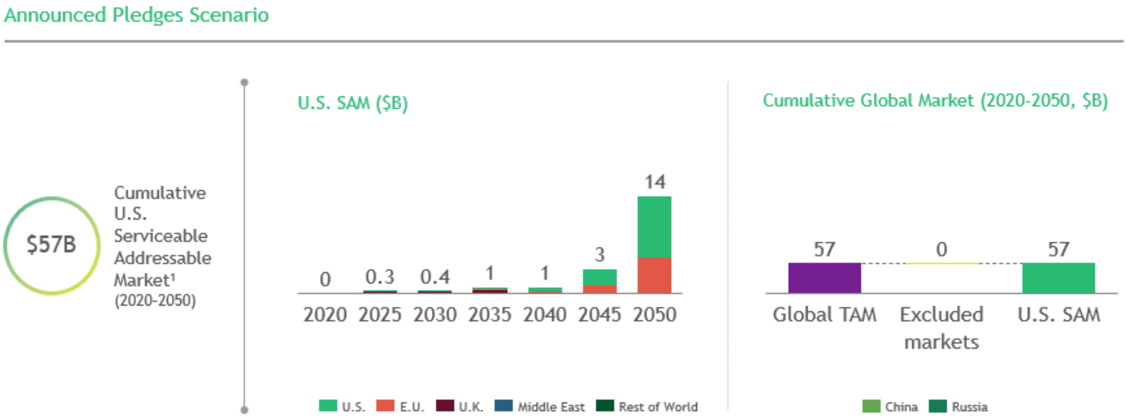

Figure 8.4 - Project Development annual market value, Announced Pledges Scenario (APS)

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[23] Future Prospects of Direct Air Capture Technologies: Insights From an Expert Elicitation Survey

- In NZE, the U.S. SAM comprises ~75-85% of global TAM, with the remaining ~15-25% in inaccessible markets such as Russia and China. Under APS, the U.S. SAM comprises ~100% of global TAM
- The EU, U.K., and U.S. markets retain value across NZE and APS scenarios, providing additional certainty in both domestic and export market prioritization
- The Middle East region and all other markets have ~0% market size in APS & STEPS, requiring policy intervention to drive growth
- Unlocking export market value is dependent on U.S.-based DAC technology achieving target cost reductions via increased efficiencies in carbon capture, energy use, plant design, and systems integration
- U.S. SAM for DAC across value chain segments peaks in 2045-2050 with projected ramp-up to meet net-zero targets

8.3.2 Transport & storage and Offtake

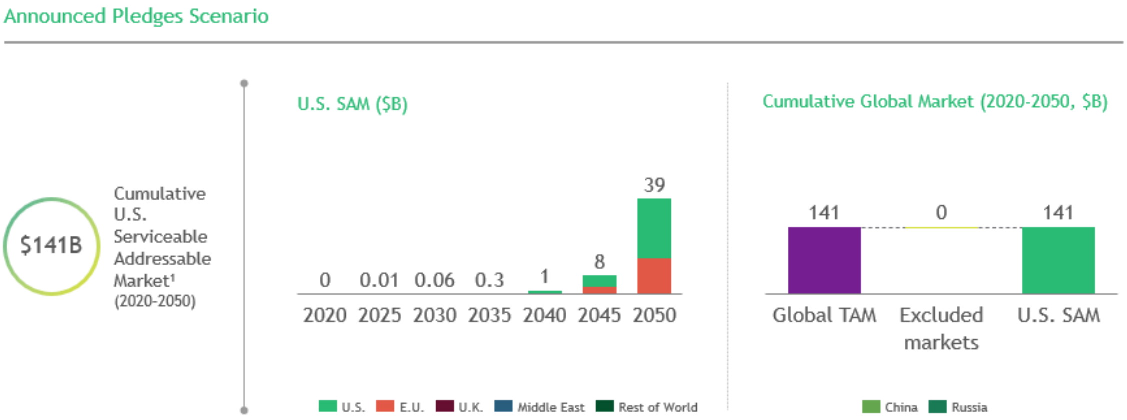

Figure 8.5 - Transport & Storage annual market value, Announced Pledges Scenario (APS)

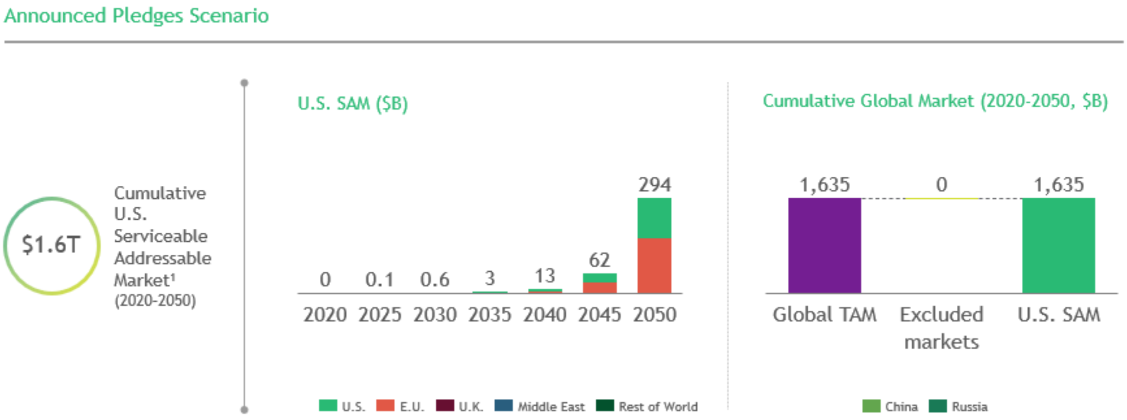

Figure 8.6 - Offtake annual market value, Announced Pledges Scenario (APS)

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- High domestic storage market value indicates strong potential for DAC capability and carbon credit generation through storage (i.e., offtake)

- Transport and storage export market, including expertise in and equipment for CO2 injection, will be lower than domestic storage use
- Offtake is projected to be 60% carbon credits and 40% synfuels
- Offtake demand is expected to be high domestically and from nations with aggressive net-zero targets
- Developed nations historically responsible for emissions may use offtake to address legacy emissions, potentially further increasing the offtake market size

8.3.3 EPC

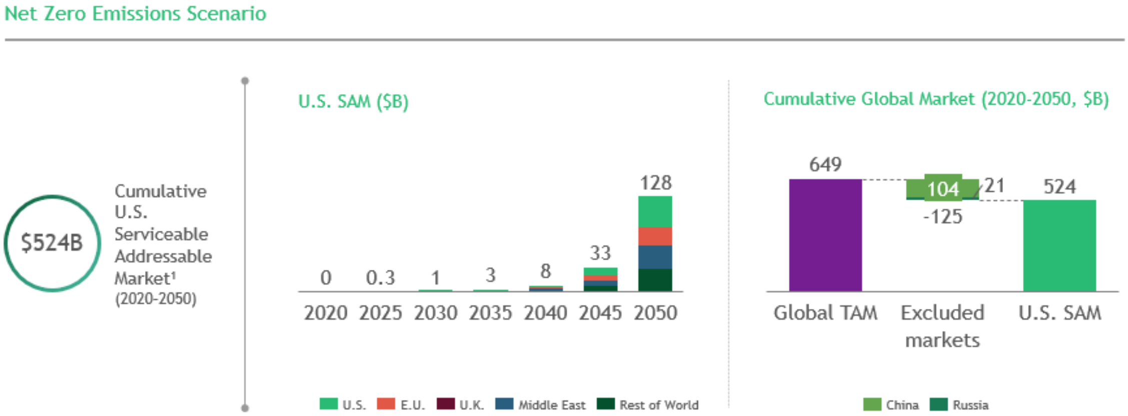


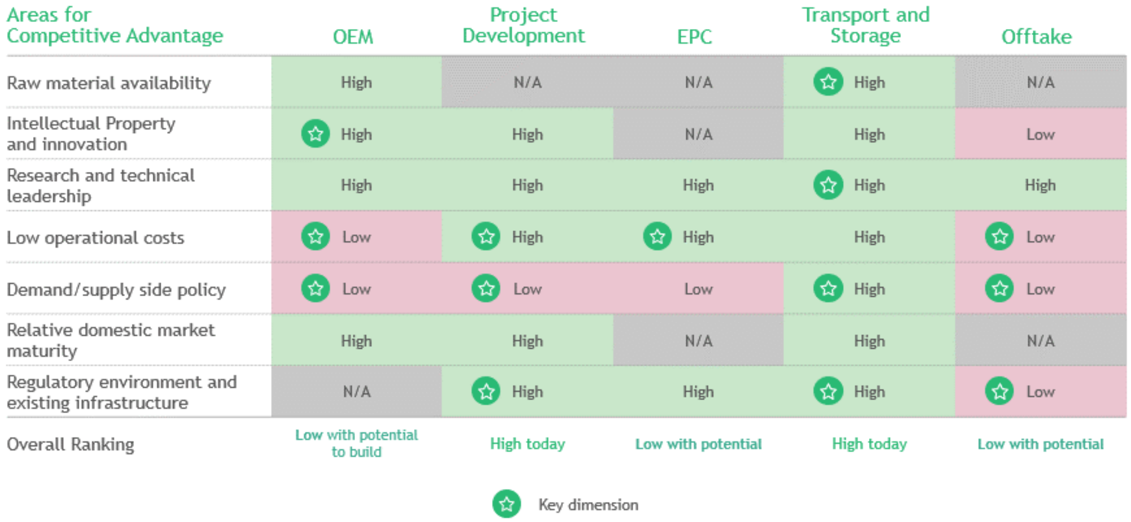
Figure 8.7 - EPC annual market value, Net Zero Emissions Scenario (NZE) See table 7.1 for explanation of NZE usage in EPC

- EPC is largely performed by local operators, so the U.S. domestic market is the primary EPC market opportunity
- Significant export of EPC capabilities is only expected for the Middle East region, where the oil and gas industry has previously imported EPC due to an imbalance in work and available engineers

8.4 Overview of competitiveness

Figure 8.8 summarizes U.S. competitive advantage across the 5 prioritized segments for Direct Air Capture. Current U.S. competitive advantage is classified as “High” or “Low” (see Figures 3.1 and 10.3 for methodology), with a summary ranking in the final row that is used for plotting in Figure 10.12. Recommendations focus on key dimensions of competitive advantage, denoted by the green star, because these dimensions must be unlocked to create durable competitive advantage. Explanations of competitive advantage ranking and key dimensions by value chain segment can be found in the main text.

- <u>Raw material availability (High):</u> The U.S. has abundant geologic storage in both saline aquifers and depleted oil wells, which is critical for carbon sequestration in DAC. Geologic carbon storage potential surveys have been conducted in limited regions across the globe, which constrains regions for direct comparison of storage potential. Surveys of the U.S. shows potential for ~3,000 Gt of geologic storage[24], an immense amount of storage for a technology projected to reach global capacity of ~3 Gt/yr in APS.



Areas for Competitive Advantage	OEM	Project Development	EPC	Transport and Storage	Offtake
Raw material availability	High	N/A	N/A	☆ High	N/A
Intellectual Property and innovation	☆ High	High	N/A	High	Low
Research and technical leadership	High	High	High	☆ High	High
Low operational costs	☆ Low	☆ High	☆ High	High	☆ Low
Demand/supply side policy	☆ Low	☆ Low	Low	☆ High	☆ Low
Relative domestic market maturity	High	High	N/A	High	N/A
Regulatory environment and existing infrastructure	N/A	☆ High	High	☆ High	☆ Low
Overall Ranking	Low with potential to build	High today	Low with potential	High today	Low with potential

☆ Key dimension

Figure 8.8 - Current U.S. competitive advantage across key areas, by segment

- <u>Intellectual Property & Innovation (High):</u> The current leading OEM is Switzerland-based Climeworks, which has the highest patenting activity at double the next leader. However, 5 of the top 12 parent producing companies are U.S.-based and the U.S. has the highest literature publication rates for DAC, at 25% greater than China. Growing activity from U.S.-based OEMs and leading direct public funding for DAC create competitive advantage for the U.S.

- <u>Research & Technical Leadership (High):</u> A strong presence of synergistic industries and related experts can increase efficiency in DAC deployment and operations. The U.S. has many engineers/technicians with relevant expertise and technical training that could transfer their skills to DAC operation (e.g., geologic injection, pipeline operations).

- <u>Low operational costs (Mixed):</u> Solid sorbent carbon capture medium and overall costs for producing DAC offtake are currently expensive for all global DAC players. The lowest cost and most effective of both OEM and offtake will likely be adopted or used more broadly, so it is critical to achieve low operational costs. Project development costs for DAC incorporate affordable co-located renewable energy, which the U.S. is well-positioned to develop with its significant solar and wind resources. More experienced EPC players are more likely to win a contract due to their cost and time savings potential for construction. Globally-leading EPC players are based in the U.K. (e.g., Petrofac), South Korea (e.g., Saipem, Hyundai Heavy), Australia (Worley), and the U.S. (e.g., Bechtel, Fluor, KBR).

- <u>Demand/supply side policy (Mixed):</u> DAC demand side policies are critical for creating robust demand that de-risks investment in DAC technology innovation and DAC facility deployment for OEMs and project developers. Sweden has the most developed plan for

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[24] National Assessment of Geologic Carbon Dioxide Storage Resources—Results

public commitment to incorporate negative emissions technology in its carbon tax scheme[25]. Demand policies importantly can guarantee offtake in early-stage development of nascent technologies that enables cost reductions through economies of scale. Supply side policies that reduce barriers for carbon storage can facilitate DAC credit creation and overall deployment. The U.S. has existing policies, including 45Q, that provides tax credits per tCO_2 stored.

- Regulatory environment & existing infrastructure (Mixed): Complex infrastructure is necessary for DAC facilities and, for smaller OEMs, this can create a significant barrier to deploying their technology. Centralized project development infrastructure can enable cost-sharing, reduce logistical barriers like permitting, and accelerate piloting of nascent DAC technologies. The U.S. is the only country publicly-funding centralized infrastructure for 4 DAC hubs funded in IIJA that will include pipelines, compressors, and storage injection. This will enable project development of DAC and CO_2 storage. No country has a clear advantage in an existing infrastructure for offtake, though the EU has an Emissions Trading System and the U.S. has California's Low Carbon Fuel Standard that allows for trade/purchase carbon credits. A standardized, mature marketplace for DAC credit trades and purchases is necessary for any country hoping to unlock offtake, the largest value chain segment.

8.5 Summary of findings

Commercial-scale deployment of Direct Air Capture in the U.S. faces challenges technology-wide and for each of the 5 prioritized value chain segments. These challenges limit the potential development of a domestic market and export competitiveness for U.S. DAC players. A robust domestic market with largescale development of DAC is necessary for DAC to become economically-viable following cost reductions through learnings and economies of scale.

Technology-Wide (**including Offtake**): The U.S. is well positioned to lead the development of DAC at scale due to the presence of required geological storage formations, affordable renewable/low-carbon energy potential and technology, and skilled labor from synergistic industries (e.g., oil and gas). The U.S. has immense potential for geologic storage (~3,000 Gt) in both saline aquifers and depleted oil wells, which is much greater than storage potential in the EU (~500 Gt), the current leader in DAC deployment[26]. Despite a strong competitive advantage for the U.S., DAC policies and investments are rapidly developing globally, especially in the EU and U.K. The U.S. must continue investment, policy creation, and innovation, especially in next-generation DAC technologies, to maintain its lead.

Challenge A: To effectively sell different quality carbon credits, global carbon markets should have standardized verification and valuation of credits. DAC credits have higher permanence and quantifiability than other carbon offsets and, accordingly, higher costs for creation. Unless broader carbon markets value these differences in quality, buyers are more likely to purchase cheaper, low-quality offsets. To realize U.S. export potential, carbon markets must also allow for cross-border trade. Selection of potential actions:

- Support development of mature carbon markets: Carbon marketplaces that standardize carbon credits can address credit differentiation and encourage sales in foreign markets.

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[25] Vägen till en klimatpositiv framtid
[26] Europe Could Store Over Three Centuries' Worth of Carbon Emissions

A standardized market that reflects differences in offset quality and costs de-risks the market for buyers and can increase DAC demand. Example levers may include:
  - Establish public offset quality and verification standards for DAC carbon credits and encourage alignment on these with main export partners to enable trade
  - Support and/or partner with third-party entities to establish quality and verification standards for carbon credits that address differentiation (e.g., permanence, resource intensity)

Challenge B: High risks of not recouping investments with nascent DAC technology and offtake market discourage OEMs and project developers from investing in or developing DAC facilities. By enabling commercial-scale DAC and supporting more innovative technology and plant design, cost reductions can be achieved via increased efficiencies and economies of scale. Selection of potential actions:

- De-risk DAC deployment and investment: Increased and reliable demand for DAC offtake (credits and CO_2 for utilization) de-risks DAC facility development and technology innovation investment. Example levers may include:
  - Support long-term, secure demand for DAC offtake (e.g., government procurement agreements)
  - Strengthen emissions policies to increase private demand for DAC offsets or CO2 utilization (e.g., scope 3 emissions reporting requirements, emissions penalties)
  - Continue encouraging carbon sequestration (e.g., tax credits)

Challenge C: High energy requirements for DAC (7-15 GJ/tCO_2, Third Derivative[27]) and the goal of DAC to result in the greatest negative emissions requires largescale, affordable low (bias towards zero)-carbon energy. Steep CapEx/OpEx costs for additional creation of renewable or low-carbon energy facilities can discourage investors to finance DAC projects and then limit deployment, due to fear of not recouping their investment. Selection of potential actions:

- Support quickly scaling affordable clean energy: To minimize transmission costs and preserve DAC value by limiting emissions, renewable or low (bias towards zero)-carbon energy facilities should be co-located with DAC. Example levers may include:
  - Support accelerated project development for co-located energy facilities
  - Continue encouraging development of renewable energy facilities via incentives

OEM: While current major OEM players are not U.S.-based, the U.S. has emerging competitive advantage with domestic next generation OEMs (e.g., Heirloom, Sustaera, Verdox). Globally, the U.S. leads research on carbon capture and patent creation and has the second-highest level of private investment in OEM. Switzerland has the highest private investments, at ~4x the U.S.

Challenge D: High costs due inefficient carbon capture technology and plant design discourage investment in scaling DAC deployment. Solid sorbent medium comprises up to 55% of total solid DAC facility Capex (Third Derivative[28]), but have short lifetimes and inefficient carbon capture. Sorbents and inefficient plant design contribute significantly to the high prices for production of DAC credits or CO_2 for utilization, estimated at \$500-1,200/tCO_2[29]. Selection of potential actions:

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[27] Insight Brief #1, Direct Air Capture: Capitalizing on the Defining Decade for Technology Development

[28] Insight Brief #1, Direct Air Capture: Capitalizing on the Defining Decade for Technology Development

[29] Techno-Economic Assessment of CO2 Direct Air Capture Plants

- Support innovation of carbon capture technology and plant design: Increased carbon capture efficacy, energy efficiency, and durability will decrease costs of this capital-intensive value chain segment. Further, effective capture technology provides a significant export opportunity to other countries that are expanding their negative emissions technology uptake to meet net-zero goals. Example levers may include:
    - Continue support of IP R&D for next-generation DAC technology with higher efficacy and energy efficiency (e.g., DoE Funding Program)
    - Support increased research collaboration among national labs, universities, and private sector for cutting-edge IP

Project Development: The U.S. has a strong existing advantage in DAC project development due to its access to critical resources, a mature market, and a strong workforce. The U.S. can further build on its early-mover advantage[1] with a strong workforce of experienced developers in synergistic industries (e.g., oil & gas, CCUS) who can streamline design and deployment, and accelerate learnings for cost-reduction and effective plant design.

Challenge E: Complex site selection and infrastructure requirements for DAC facilities create financial and logistical hurdles, especially for smaller OEMs, to pilot DAC technologies at commercial scale. Strategic planning and investments that enable OEMs and project developers to create commercial-scale facilities or pilot more energy-efficient DAC technologies can help move DAC down the cost curve quickly. The barrier of high costs for planning and creating DAC facilities could limit the ability of emerging OEMs to pilot promising DAC technologies and potentially realize critical cost reductions for DAC. Selection of potential actions:

- Continue supporting centralized domestic project development (e.g., U.S. DAC hubs): Centralized project development de-risks project development, facilitates cost sharing, and enables industrial-size applications of next-generation OEM technology. These benefits result in decreased costs (development and operating) and increased cost competitiveness of DAC credits or CO2 for utilization. The U.S. currently is the only country publicly funding DAC hubs. Example levers may include:
    - Support various project development needs, including permitting and energy access; infrastructure (e.g., compressors, pipelines, and plumbing); and community engagement
    - Enable diverse DAC technologies with centralized infrastructure to support broad innovation that could achieve significant DAC cost reductions

- Reduce barriers for DAC facility location selection: Site selection for DAC facilities must include ideal environmental conditions, potential for renewable energy access, and capacity for storage for scaling. Selection should also encompass societal impacts (e.g., jobs potential). Smaller OEMs of nascent DAC technology have more limited capacity for these extensive surveys that are needed to develop commercial DAC. Example levers may include:
    - Support site selection surveys to identify ideal locations for DAC facilities

Transport and Storage: The U.S. has a strong existing advantage in transport and storage due to storage potential, relevant skilled labor and technology, and mature public funding. There is also immense potential for geologic storage in the U.S. (~3,000 Gt,[30], coupled with oil and gas industry expertise and technical capability for reliable and cost-effective CO_2 sequestration.

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[30] National Assessment of Geologic Carbon Dioxide Storage Resources – Results

Challenge F: Long timelines to secure storage permitting can stall DAC deployment and limit the ability of the U.S. to achieve early mover advantage for DAC. As of May 2022, only 2 class VI wells have been permitted by the EPA and the process has been reported to take about 6 years[31]. This delay causes risk for OEMs and project developers that discourages their investment in commercial scale deployment. Early DAC players can achieve cost reductions and efficiencies that enable them to outcompete new entrants, thus creating a durable competitive advantage. Selection of potential actions:

- Streamline CO_2 storage permitting for DAC facilities –Despite the abundant geological storage in the U.S., the ability of DAC to take advantage of this storage can be limited by long timelines or an inability to secure sequestration permits. Example levers may include:
    - Support accelerated processes for permits, environmental impact, and zoning to enable faster deployment and scaling of DAC

EPC: The U.S. has a path to leadership in EPC with the greatest opportunity in the domestic DAC market across scenarios and in the Middle East if the region targets net-zero by 2050 (i.e., net-zero scenario). U.S. EPCs have relevant skilled labor and technology from synergistic industries (e.g., O&G) that could be capitalized on to become leading DAC EPC providers.

Challenge G: Due to the nascency of DAC, EPC players do not yet have experiences that will help them to become preferred DAC facility contractors. The first commercial DAC plant to be created in the U.S. is contracted to Worley, an Australian EPC player[32]. U.S.-based EPC players must gain experience with DAC to enable efficient and cost-effective DAC facility creation and further drive down domestic DAC production costs. Selection of potential actions:

- Support early learning by domestic EPC players: There is potential for early-mover advantage, in which EPCs with experience in DAC facility creation are likely to be preferentially selected due to cost and construction time savings. Example levers include:
    - Encourage OEMs and project developers to contract domestic EPCs
    - De-risk commercial-scale implementation based on nascency of different DAC technologies (e.g., low-cost project financing to accommodate extended project timelines)

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[31] The Permitting Program Crucial for Carbon Capture's Success

[32] 1PointFive Selects Worley to Engineer Direct Air Capture Facility

9 Advanced Nuclear SMRs

Advanced nuclear small modular reactors (SMRs) can provide zero-carbon firm generation at potentially lower costs and enhanced safety than traditional nuclear reactors. In this study, SMRs encompass both light water reactor (LWR) designs and advanced Gen IV reactor designs, such as Sodium Fast Reactors (SFRs), High Temperature Gas-cooled Reactors (HTGRs), and Molten Salt Reactors (MSRs). Some technologies, such as HTGRs, can go beyond producing power and also provide industrial heat for creating clean steel or hydrogen electrolysis. The modular nature and enhanced passive safety features of advanced nuclear SMRs provide more deployment flexibility than conventional reactors, allowing SMRs to power remote communities, military facilities, or microgrids.[33]

It is important to note that this study generally focused on both LWR- and Gen IV-based SMRs, up to ~300 – 400 MW per unit, rather than large, GW-scale Gen III or Gen IV reactors. This distinction was due to differences in the underlying value chain and drivers of competitive advantage, largely that SMRs are generally envisioned to be mass-produced in a factory setting to capture economies of volume, while GW-scale reactors depend more on cost discipline from large capital project management. GW-scale reactors are expected to be built using both Gen III and Gen IV technologies in Asia and other markets with significant electricity demand growth and relatively robust transmission grids. Western markets, however, are expected to rely more heavily on SMRs to balance the grid as generation sources such as coal are retired. The U.S. in particular is expected to rely more heavily on SMRs due to recent high-profile GW-scale projects which have gone significantly over budget, with lengthy delays.

9.1 Overview of value chain segments considered for this study

The advanced nuclear small modular reactor value chain, detailed in appendix slide 114, is displayed below. Many elements of the fuel supply chain, including uranium mining, processing, and enrichment, were included in the raw materials segment.
In assessing areas for deep-dive analyses, the study focused on three areas:

1. **Raw materials**, which are largely focused on uranium mining and enrichment, are a critically important piece of the advanced nuclear SMR value chain. The high concentration of ore and enrichment capacity in a small set of countries creates potential to build competitive advantage, with ~60% of global mining capacity held by just three countries (Kazakhstan, Australia, and Namibia) and over 40% of enrichment capacity held by Russia alone.[34] In addition, the strategic non-proliferation considerations of owning a significant portion of uranium mining, enrichment, and fuel fabrication drive potential geostrategic benefits

2. **OEM** is a clear space for U.S.-based companies to enter and compete. There is high market value potential and significant opportunity to generate a durable competitive advantage in spaces like reactor module components, completed reactor modules, technology-specific fuel fabrications, or IP licensing

3. **EPC** is another early area of focus due to the high market value and significant overlap with the OEM-driven engineering activities. Outside of significant OEM participation in the engineering portion of EPC, local contractors largely drive the construction

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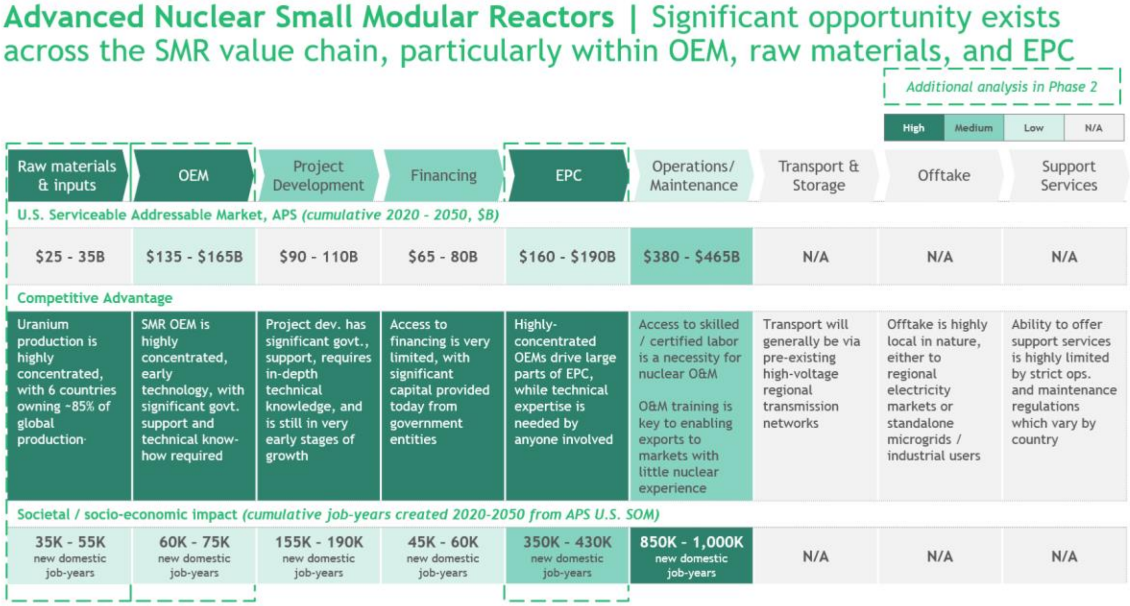
[33] Small Modular Power Reactors

[34] Uranium Enrichment; World Uranium Mining Production



Advanced Nuclear Small Modular Reactors | Significant opportunity exists across the SMR value chain, particularly within OEM, raw materials, and EPC

Additional analysis in Phase 2

High | Medium | Low | N/A

Raw materials & inputs	OEM	Project Development	Financing	EPC	Operations/ Maintenance	Transport & Storage	Offtake	Support Services
U.S. Serviceable Addressable Market, APS *(cumulative 2020 - 2050, $B)*								
$25 - 35B	$135 - $165B	$90 - 110B	$65 - 80B	$160 - $190B	$380 - $465B	N/A	N/A	N/A
Competitive Advantage								
Uranium production is highly concentrated, with 6 countries owning ~85% of global production·	SMR OEM is highly concentrated, early technology, with significant govt. support and technical know-how required	Project dev. has significant govt., support, requires in-depth technical knowledge, and is still in very early stages of growth	Access to financing is very limited, with significant capital provided today from government entities	Highly-concentrated OEMs drive large parts of EPC, while technical expertise is needed by anyone involved	Access to skilled / certified labor is a necessity for nuclear O&M O&M training is key to enabling exports to markets with little nuclear experience	Transport will generally be via pre-existing high-voltage regional transmission networks	Offtake is highly local in nature, either to regional electricity markets or standalone microgrids / industrial users	Ability to offer support services is highly limited by strict ops. and maintenance regulations which vary by country
Societal / socio-economic impact *(cumulative job-years created 2020-2050 from APS U.S. SOM)*								
35K - 55K new domestic job-years	60K - 75K new domestic job-years	155K - 190K new domestic job-years	45K - 60K new domestic job-years	350K - 430K new domestic job-years	850K - 1,000K new domestic job-years	N/A	N/A	N/A

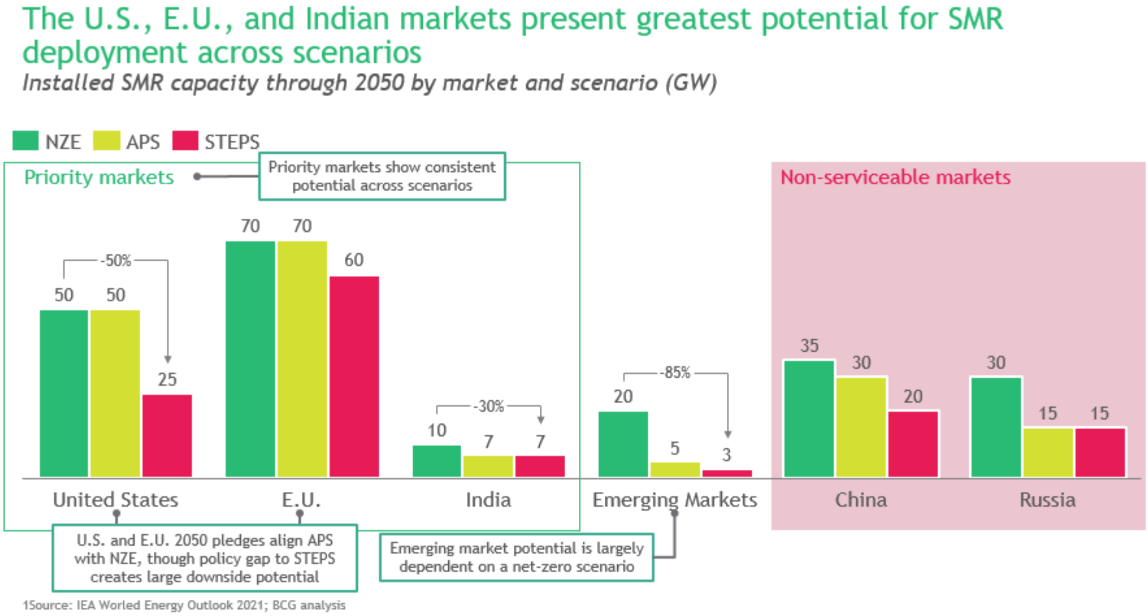
Figure 9.1 – Advanced Nuclear SMR Value Chain Prioritization Results

With a lower market value and competitive advantage potential, **project development** was not prioritized in this analysis. **Financing** was also deprioritized, due to its relatively low market potential, as were segments such as **O&M**, **transport and storage**, and **offtake** because of the largely local nature of the work.

9.2 Size of the opportunity in domestic market and exports

The U.S. and EU markets are expected to be the largest opportunities for U.S.-based SMR players, followed by India.

The U.S. Serviceable Addressable Market (SAM) for advanced nuclear SMRs is expected to range from 150 - 160 GW of total installed capacity under APS (120 - 210 STEPS to NZE) by 2050, up from <1 GW today. This reflects ~$450 – 550B in total capital deployed. The U.S. SAM is expected to be led by the E.U. market of 65 - 75 GW or $200–250B, followed by the U.S. at 45 - 55 GW or $140–180B and India at 6 - 8 GW or $20-25B.


The U.S., E.U., and Indian markets present greatest potential for SMR deployment across scenarios

Installed SMR capacity through 2050 by market and scenario (GW)

Priority markets show consistent potential across scenarios

U.S. and E.U. 2050 pledges align APS with NZE, though policy gap to STEPS creates large downside potential

Emerging market potential is largely dependent on a net-zero scenario

1Source: IEA Worled Energy Outlook 2021; BCG analysis

Figure 9.2 – Cumulative Deployment Potential by Priority Market

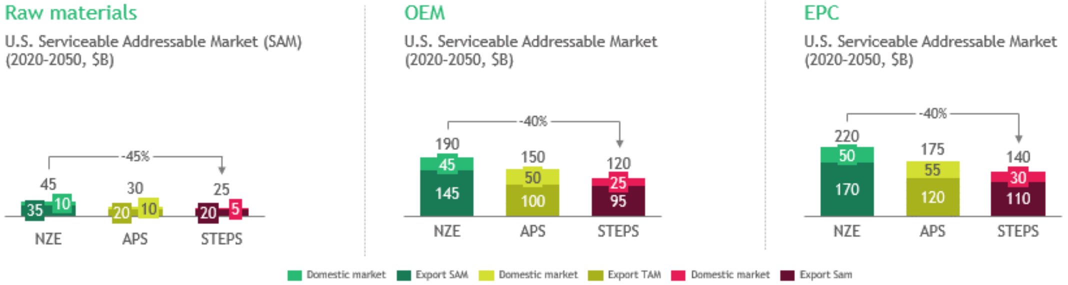


Figure 9.3 – U.S. Serviceable Addressable Market by Value Chain Segment

It is important to note that the figures here, based on IEA projections, are inherently conservative if advanced nuclear SMRs are able to achieve targeted cost reductions from economies of volume. Other publications, such as the BloombergNEF's New Energy Outlook 2021 Red Scenario, which includes optimistic nuclear assumptions, estimate the potential at over 10x the global 2050 installed nuclear capacity as the IEA APS. Similarly, the Princeton Net Zero America report and analysis from the Breakthrough Institute estimate that with optimistic nuclear assumptions, total U.S. nuclear capacity could be ~2–4x higher than the IEA APS scenario. Thus, the market values and export potential in this study should be viewed as a lower-bound estimate with significant upside potential.

The U.S. Serviceable Obtainable Market (SOM), which reflects the portion of the global market which U.S.-based companies could realistically capture, is estimated to be 20 – 30% based on precedents set in the conventional nuclear industry. The lower bound of the range is based on the historical proportion of global nuclear plants designed by U.S. companies, while the upper bound is based on the global leader in global nuclear projects currently under construction, which is China.[35] This range reflects the spread of market share which the U.S. could potentially capture, with the lower bound (~20%) reflecting business as usual without strategic support while the upper bound (~30%) reflects what a market leader could capture. U.S.-based players, particularly in the OEM space, can achieve or exceed upper bound market share by building a competitive moat through early leadership in technology quality, capturing economies of scale in manufacturing, and ensuring access to key export markets.

Because nuclear is a highly sensitive technology, several markets were considered non-addressable for the U.S. in this study, including China, Russia, and all countries on the Nuclear Regulatory Commission (NRC) embargoed list. Of these, China is by far the largest potential market, with 25-30 GW.

Priority Markets	Segments included in SAM	Relevant drivers for breakout
European Union	Raw materials OEM EPC	• The E.U. has one of the largest nuclear fleets in the world, led by France • As a customs union, trade potential is similar across the E.U., with some variation between pre-enlargement and former Soviet states which historically used Soviet nuclear technology • Significant nuclear capacity additions through 2050 are expected to drive significant need for fuel inputs, OEM, and EPC services
India		• India's nuclear capacity is expected to grow significantly through 2050 from low levels today • Little domestic SMR capabilities present opportunity for U.S. companies to enter the market and participate in the country's nuclear growth, including imports of fuel, OEM designs / components, and EPC services • Note: India is currently on the NRC list of Restricted Destinations, requiring an export license for a subset of exports
Emerging Markets[36]		• With little existing nuclear today, emerging markets are expected to demonstrate significant nuclear capacity growth through 2050 • Due to a general lack of domestic nuclear capabilities, growth in nuclear will largely be served by imports from other countries, such as the U.S. • SMRs hold particular promise for emerging markets due to lower capital barriers, reduced safety / O&M needs, and modular capacity additions which can more easily be incorporated into growth electrical grids

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[35] Global Battery Arms Race: 200 Gigafactories; China Leads

[36] Emerging markets refers to multiple countries as defined by the IEA, which includes over ~140 countries and is defined as all non-OECD countries, excluding Bulgaria, Croatia, Cyprus, Malta, and Romania. This analysis further excludes China and Russia due to lack of market access and India to avoid double-counting

Inaccessible Markets	Excluded Segments	Relevant Drivers for Exclusion
China	Raw materials OEM EPC	• U.S. has put dual-use export controls into place for both nuclear technology and radioactive materials • China has devoted substantial resources to build up state-owned nuclear companies (e.g., China National Nuclear Corp.)
Russia		• U.S. dual-use export controls • Russia has devoted substantial resources to build up state-owned nuclear companies (e.g., Rosatom) • Current sanctions on Russia prohibit U.S. investment in the country
NRC Embargoed Countries[37]		• The U.S. Nuclear Regulatory Commission (NRC) has restricted any exports of nuclear material or equipment to the following countries under an NRC

Table 8.1 – Priority and Inaccessible Markets

9.3 Segment level analysis

9.3.1 Raw materials

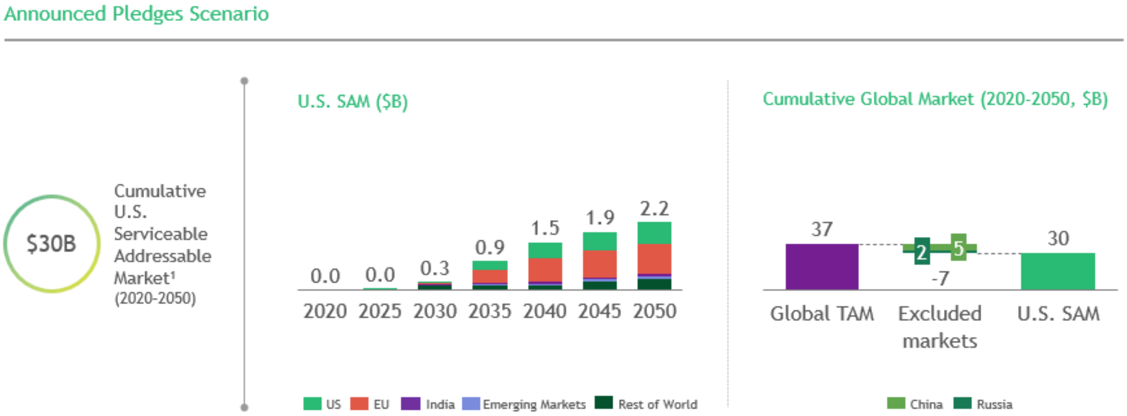

Figure 9.4 – U.S. Raw Materials Serviceable Addressable Market by Year (APS)

- U.S. SAM comprises ~60-70% of global TAM, with remaining ~30-40% in inaccessible markets such as Russia and China
- U.S. SAM for raw materials loses 50–60% of market value outside of the NZE, with emerging markets losing the majority of value
- Investment in U.S. domestic enrichment capacity can serve legacy generation fleets as well as future large-scale reactors, providing additional upside and market certainty

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[37] Includes Cuba, Iran, Iraq, North Korea, Sudan, and Syria

- Relatively high margins for uranium enrichment (~30-60%) drive margin pools which are comparable to other prioritized segments

9.3.2 OEM and EPC

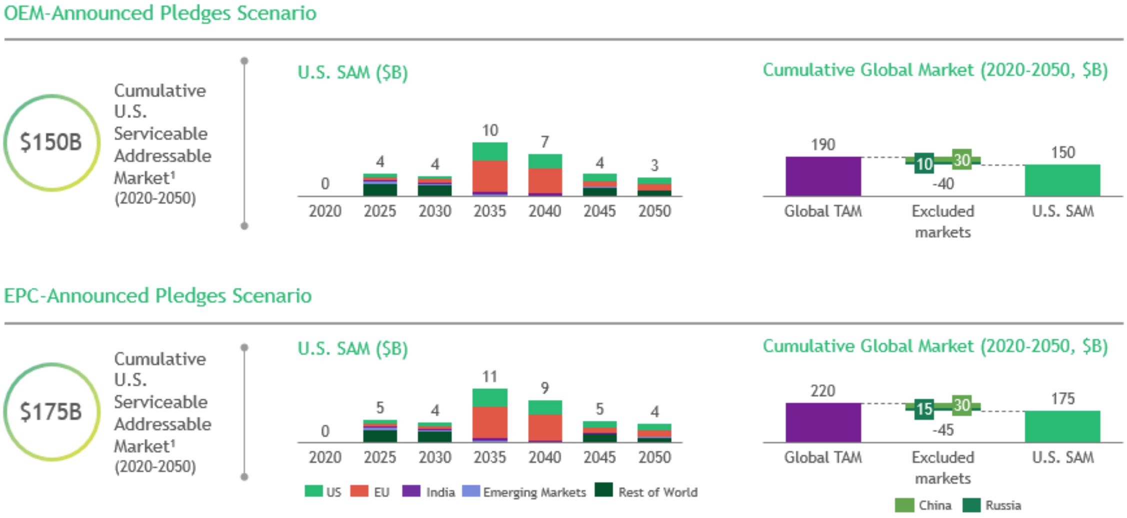
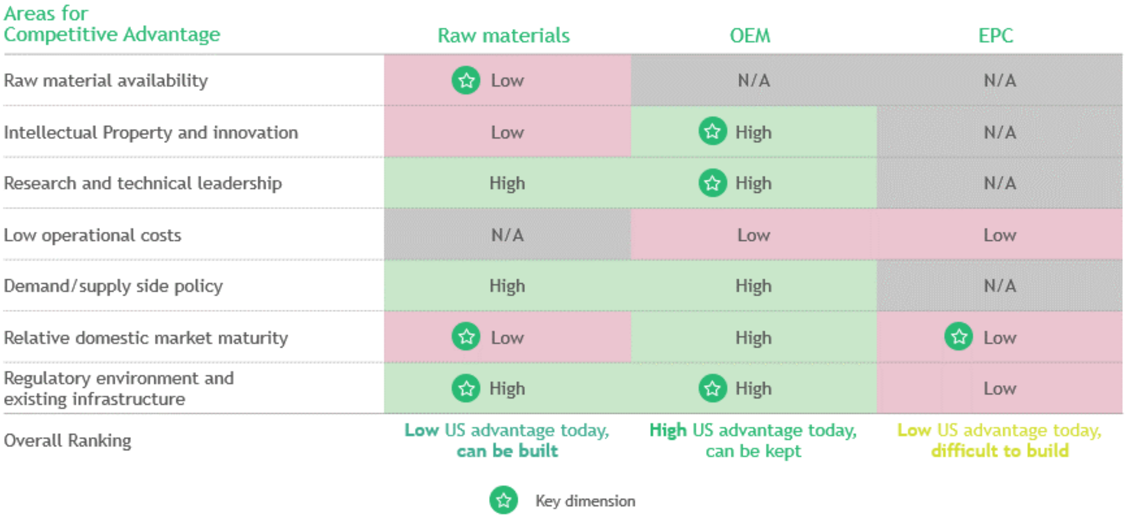


Figure 9.5 – U.S. OEM and EPC Serviceable Addressable Market by Year (APS)

- U.S. SAM comprises ~60-70% of global TAM, with remaining ~30-40% in inaccessible markets such as Russia and China
- The E.U. and Indian markets retain significant value across scenarios, providing additional certainty in export market prioritization
- Emerging markets lose majority of value outside the NZE, requiring unlikely policy intervention to drive growth
- Unlocking export market value is dependent on U.S. SMRs achieving target cost reductions and complying with nuclear regulatory schemes abroad
- U.S. SAM for SMR OEM and EPC peaks in ~2030–2040, leaving limited time to unlock export potential in priority high-growth markets

9.4 Overview of Advanced Nuclear SMR Competitiveness

Figure 9.6 below summarizes U.S. competitive advantage across the three prioritized segments, raw materials, OEM, and EPC. Current U.S. competitive advantage is classified as “High” or “Low” (see Figures 3.1 and 10.3 for methodology), with a summary ranking in the final row that is used for plotting in Figure 10.12. Recommendations focus on key dimensions, denoted by the green star, because these dimensions must be unlocked to create durable competitive advantage. Explanations of competitive advantage ranking and key dimensions by value chain segment are included below.



Areas for Competitive Advantage	Raw materials	OEM	EPC
Raw material availability	✪ Low	N/A	N/A
Intellectual Property and innovation	Low	✪ High	N/A
Research and technical leadership	High	✪ High	N/A
Low operational costs	N/A	Low	Low
Demand/supply side policy	High	High	N/A
Relative domestic market maturity	✪ Low	High	✪ Low
Regulatory environment and existing infrastructure	✪ High	✪ High	Low
Overall Ranking	**Low** US advantage today, **can be built**	**High** US advantage today, can be kept	**Low** US advantage today, **difficult to build**

✪ Key dimension

Figure 9.6 – U.S. Current Competitive Advantage by Segment

Key advanced nuclear SMR competitiveness findings include:

- <u>Raw Material Availability (Low)</u>: The U.S. currently is estimated to hold <1% of global uranium reserves and currently enriches <10% of global nuclear fuel. Uranium mining is currently dominated by Kazakhstan, which owns ~40% of mining capacity, while Russia owns ~45% of global enrichment capacity.[38]

- <u>Intellectual Property & Innovation (High)</u>: IP is critical for the OEM segment and the U.S. is currently the global leader in SMR-related patents, with ~25% more patents than the next highest country, China. The U.S. also ranks 2nd in patents related Gen IV advanced nuclear, behind China by ~4x but ahead of South Korea (ranked 3rd) by ~2x.

- <u>Research & Technical Leadership (High)</u>: Also critical for the OEM segment, the U.S. leads publication of SMR-related research papers. U.S. institutions, led by the DOE and Idaho National Laboratory, published 20 - 30% more SMR-related research papers 2015 – 2021 than the next-closest leader, China. Further, the U.S. papers earned a higher score on the citation index, which can be viewed as a proxy for paper quality based on the number of times it is cited in other research papers.

- <u>Relative Domestic Market Maturity (Low)</u>: Since 2017 private investment in uranium mining or processing facilities has been led by Australia (~$330 M), Russia (~$175 M), and Australia (~$20 M), while U.S.-based companies have attracted <$1 M in investment over the same period.

- <u>Regulatory Environment & Existing Infrastructure (High):</u> This dimension was relevant for both the raw materials segment as well as the OEM segment. Both segments see significant interest from the DOE, such as the Advanced Reactor Demonstration Program (ARDP) for OEM or the ongoing DOE HALEU Availability Program, which target supporting nascent technologies and players in both areas. Further, for raw materials the

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[38] Uranium Enrichment; World Uranium Mining Production

U.S. can draw on uranium enrichment expertise from defense applications, such as the National Nuclear Security Administration (NNSA). For OEM, a robust domestic nuclear industry supported by the U.S. DOE and Nuclear Regulatory Commissions (NRC), which are generally viewed as the gold standard in nuclear research and licensing globally, gives U.S.-based companies a boost in terms of credibility and safety reputation abroad.

9.5 Summary of findings

The U.S. is well-positioned to build on early leadership in the advanced nuclear SMR space, with many private players pursuing a range of technologies and designs. However, both technology-wide and segment-specific challenges may hinder the ability of U.S. companies to build on early progress and establish a robust domestic SMR industry which would support competitive advantage against state-owned competitors in key export markets abroad.

Technology-wide: The U.S. has an opportunity to lead in advanced nuclear SMRs due to an early lead in IP/R&D, globally leading nuclear research and regulatory institutions (such as the DOE and NRC), and a robust set of private market participants. Despite this early lead, domestic progress to establish an early advanced nuclear Gen IV technologies is limited by a lack of commercial volumes of HALEU-based fuel needed for these advanced designs. Further, export potential for both advanced Gen IV SMR designs as well as conventional LWR designs is limited by a patchwork of country-specific regulations which create high barriers to entry for key export markets. If left unaddressed, these intertwined challenges limit both a potential domestic market which would allow U.S. players to prove technologies and establish scale and would in turn enable export competitiveness for U.S. players.

Challenge A: Country-by-country regulatory approvals create high barriers to entry. These country-specific regulations can threaten the core cost advantage of SMRs, the ability to mass-produce standardized reactor modules. If U.S. companies are forced to tailor products to various regulatory regimes a key driver of cost advantage may be lost, reducing export competitiveness relative to state-backed competitors. Selection of potential actions:

- Ensure export market access: Harmonizing nuclear regulations with priority export markets can help provide U.S. companies advantage by ensuring products will pass regulatory review. Further, this regulation harmonization may potentially complicate approvals for foreign competitor products, hampering competitor access. Example levers may include:
    - Harmonize regulations and licensing requirements with target markets via bilateral NRC engagement

Challenge B: Deployment of advanced Gen IV SMR technologies is limited by a "chicken or the egg" issue of HALEU fuel availability. Non-LWR-based designs, such as Gen IV technologies, require commercial volumes of HALEU production which does not exist today. Russia is the only country to produce significant amounts of HALEU, while the U.S. has only created research quantities by down-blending weapons-grade uranium. Meanwhile, nascent technology has created a "chicken or the egg" scenario, wherein insufficient demand has been proven to justify a lack of investment and financing for factory-scale production of reactor modules and HALEU-based fuels. Selection of potential actions:

- Build domestic HALEU production capacity: De-risking private investment into U.S. HALEU production capacity can help ensure an ongoing commercial supply of fuel for domestic projects and exports. Example levers may include:

    - Provide offtake guarantees to de-risk initial investment in enrichment (e.g., government procurement guarantees for initial outputs)
- Expand financing access to de-risk investment in domestic enrichment capacity (e.g., loan guarantees, cost-sharing programs, tax credits)

Raw materials: While the U.S. does not currently hold a competitive advantage in uranium enrichment due to a lack of domestic uranium production or enrichment (including HALEU), strong strategic considerations make it imperative that the U.S. further develop its domestic enrichment capabilities. These include the dependence of OEM export success on guaranteeing fuel supply and geopolitical non-proliferation concerns. Expanding domestic enrichment capability, however, requires secure uranium supply chains to overcome a lack of domestic uranium reserves and production.

Challenge C: The U.S. lacks a clear supply of uranium. As discussed in the competitiveness overview section above, the U.S. lacks domestic uranium reserves or production, both of which are largely dominated by countries such as Russia or Kazakhstan. Selection of potential actions:

- Ensure uranium supply via allies: Collaborate with trusted trade partners with significant uranium deposits or production, such as Australia or Canada. Australia produces 10-15% of global uranium and is estimated to hold ~30% of global uranium ore deposits, while Canada holds both ~10% of global production capacity and ~10% of potential ore reserves.[39] Example levers may include:
    - Facilitate partnerships for uranium supply with trusted partners (e.g., Canada, Australia)
    - Launch initiatives with coordinated joint oversight by appropriate agencies (e.g., EXIM, Treasury) to coordinate investments in key partner uranium mining operations

OEM: The U.S. holds early advantage in the OEM space, particularly in portions of IP/research and the presence of robust private players. Existing policies, such as the DOE ARDP initiative, can be further bolstered to ensure continued U.S. leadership in this strategically important space. This leadership is threatened, however, by factors which inhibit U.S. players from capturing economies of volume, growing levels of research and IP from China, and competition from state-backed competitors from Russia and China.

Challenge D: SMRs must achieve economies of volume despite regulatory, technological, and financial uncertainties. As discussed above, cost advantages of SMRs over conventional nuclear rely on economies of scale from standardized, factory-produced reactor modules. Further, most technologies are still early in the pilot phase and has not been deployed at scale to demonstrate target cost reductions. Selection of potential actions:

- Drive robust pipeline of SMR demand: Increased demand for SMR projects builds domestic advantage by enabling cost reductions through de-risked private investment in manufacturing and R&D, economies of volume, and learnings from repeated deployment. Example levers may include:
    - Incentivize or require zero-carbon energy and capacity
    - Procure SMR projects through the federal government via power purchase agreements (PPAs) or for relevant government facilities (e.g., national labs, defense)

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[39] World Uranium Mining Production

- Enable economies of volume:[40] De-risk private investment in manufacturing facilities to enable domestic players to achieve target economies of volume, a primary driver of SMR cost-competitiveness. Example levers may include:
    - Expand financing access to de-risk investment in domestic manufacturing capacity for relevant advanced nuclear components (e.g., loan guarantees, cost-sharing programs, tax credits)
    - Incentivize private domestic manufacturing investment to de-risk investment (e.g., production tax credit programs, domestic content requirements)
- Streamline project deployment: Reforming the lengthy and complicated approval processes for advanced SMR projects will de-risk projects and further increase demand, enabling advantage through cost reductions from learnings and lower-cost financing. Example levers may include:
    - Streamline domestic permitting, review, and approval timelines for SMR projects while ensuring critical safety and environmental requirements are met
    - Facilitate stakeholder engagement and education from project Phase 0 to maintain project timelines

Challenge E: The U.S. lags China in advanced reactor IP / R&D and holds a tenuous lead in SMR IP and R&D. As discussed in section 6.3, overview of competitiveness, the U.S. lags China in Gen IV advanced nuclear patents by ~4x and only holds ~25% more SMR-related patents than China. Ceding ground in the race for IP and R&D is likely to limit long-term competitiveness in the advanced nuclear SMR space. Selection of potential actions:

- Maintain U.S. lead in innovation: Continued innovation will help the U.S. maintain an early lead in IP creation and R&D, building advantage through superior technology quality and innovative cost reductions. Example levers may include:
    - Further facilitate research collaboration among national labs, universities, and the private sector
    - De-risk technology demonstrations by increasing access to financing (e.g., cost sharing programs) and streamlining NRC licensing process while maintaining highest commitment to safety. Effectiveness can be increased by crafting programs based on achieving commercialization milestones

Challenge F: U.S. players are competing against state-backed competitors. Competitors such as China and Russia are also actively researching and developing technologies in this strategically significant space, requiring further investment, innovation, and policy changes to maintain advantage. Further, these state-backed competitors are often able to extend more comprehensive product offerings than private U.S. players, including things like guaranteed fuel supply, low-interest state-backed loans, and even geopolitical negotiating items. Remaining competitive against such state-backed competitors will require U.S. players to be able to extend similar offers for table-stakes items such as fuel and financing. Selection of potential actions:

- Ensure U.S. companies can match state-backed competitor offerings: Enabling U.S. companies to match what state-backed competitors (such as Rosatom or China National Nuclear Corporation) can offer, like low-cost financing or guaranteed fuel supply, will directly increase export competitiveness. Example levers may include:

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[40] Economies of volume refers to the cost advantage provided from mass producing large numbers of standardized modules. This differs from economies of scale, which is commonly used in the nuclear industry to refer to the cost efficiencies from increasing the scale of an individual plant.

  - Facilitate spent fuel waste management programs (e.g., re-import to U.S. or third-party partner for recycling and disposal)
  - Provide low-cost project financing to facilitate exports (e.g., U.S. EXIM)

- EPC: While engineering-related EPC work is closely tied to the OEMs, the U.S. does not currently hold competitive advantage in the EPC space. Recent U.S. domestic projects, such as Vogtle and Virgil C. Summer, have gone over budget with significant delays, while competitors in China or South Korea have deployed projects successfully. Relevant recommendations are included in the technology-wide section, particularly “Support robust pipeline of SMR demand” and “Streamline project deployment.”

10 Detail on Methodology

10.1 Overview

For each technology selected, an initial analysis was performed to understand three criteria: total market value, the opportunity to build competitive advantage, and socioeconomic impact.

10.1.1 Total Market Value

Market size and margin pool projections were calculated through 2050. This was achieved by leveraging a diverse set of sources, including IEA, EDF MACC 2.0, Princeton NZA, Drawdown Report, IRENA, EIA, IPCC, BCG Centre for Energy Impact, BCG Centre for Public Impact, and BCG Centre for Mobility. For market calculations, 2021 U.S. dollar value was used to omit recent inflation.

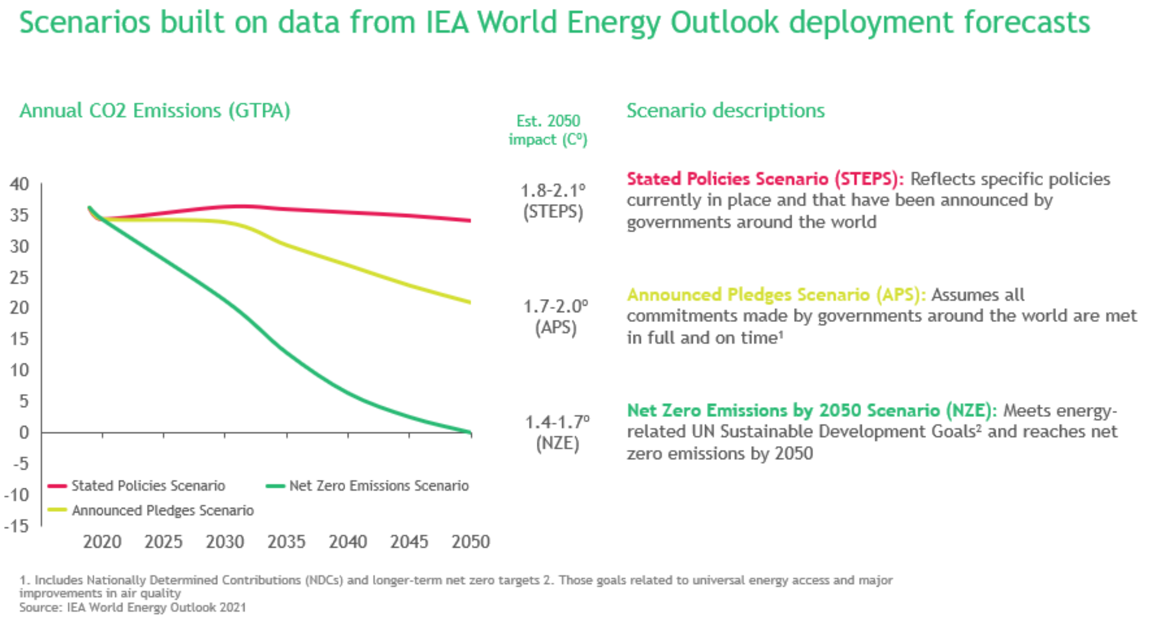
We then assessed the market opportunity for the U.S. by value chain segment in three ways:

1. Total Addressable Market (TAM) – the total market size

2. Serviceable Addressable Market (SAM) – the total market excluding countries where U.S. exports are unlikely

3. Serviceable Obtainable Market (SOM) – fraction of addressable market the U.S. could likely capture

To account for the potential variability in emissions reductions over the next 30 years, three scenarios directly tied to global emissions reductions were considered:



Stated Policies Scenario (STEPS): Reflects specific policies currently in place and that have been announced by governments around the world

Announced Pledges Scenario (APS): Assumes all commitments made by governments around the world are met in full and on time[1]

Net Zero Emissions by 2050 Scenario (NZE): Meets energy-related UN Sustainable Development Goals[2] and reaches net zero emissions by 2050

1. Includes Nationally Determined Contributions (NDCs) and longer-term net zero targets 2. Those goals related to universal energy access and major improvements in air quality
Source: IEA World Energy Outlook 2021

Figure 10.1 – IEA Scenario Overview

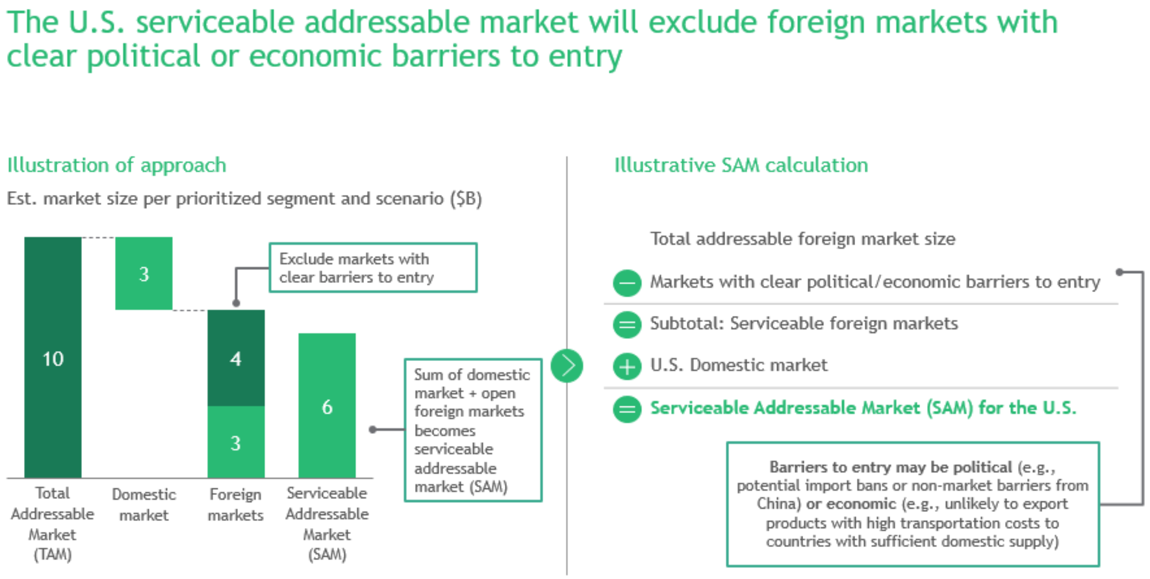


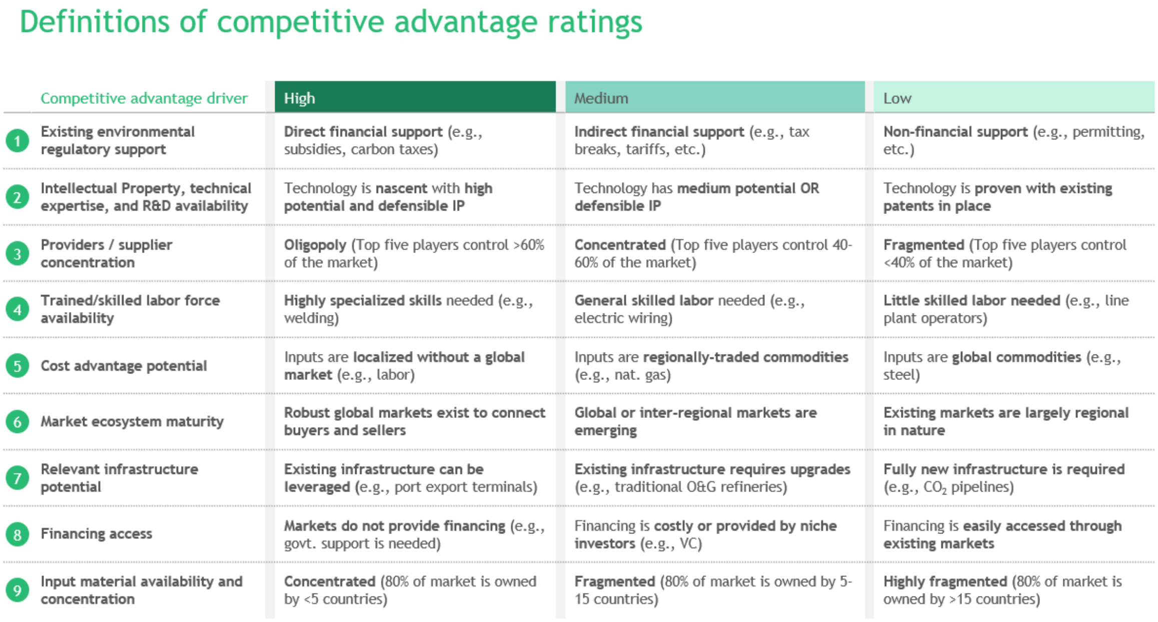
Figure 10.2 – SAM Calculation Approach

This study conducted modeling for each scenario, with comparisons and final determinations for prioritization ultimately determined using the APS track, which represents an ambitious middle target for emissions reduction. Final value chain segment-level outcomes were compared based on APS market size and competitiveness. Key insights shown here represent the APS scenario and therefore should be viewed as cautiously optimistic.

Market sizes estimated in this work are highly sensitive to a given scenario. It is imperative when considering the recommendations made in this study, to note the scenario being used to inform market sizes and competitive environments. Market sizes change considerably when moving from one scenario to another. Consistent with market size changes between scenarios, the scale and impact of specific recommendations will vary.

10.1.2 Opportunity for U.S. competitive advantage

To determine the current state of U.S. competitive advantage and the advantage held by other countries, we conducted an analysis for each technology at the value chain segment level, considering nine key potential drivers of advantage:

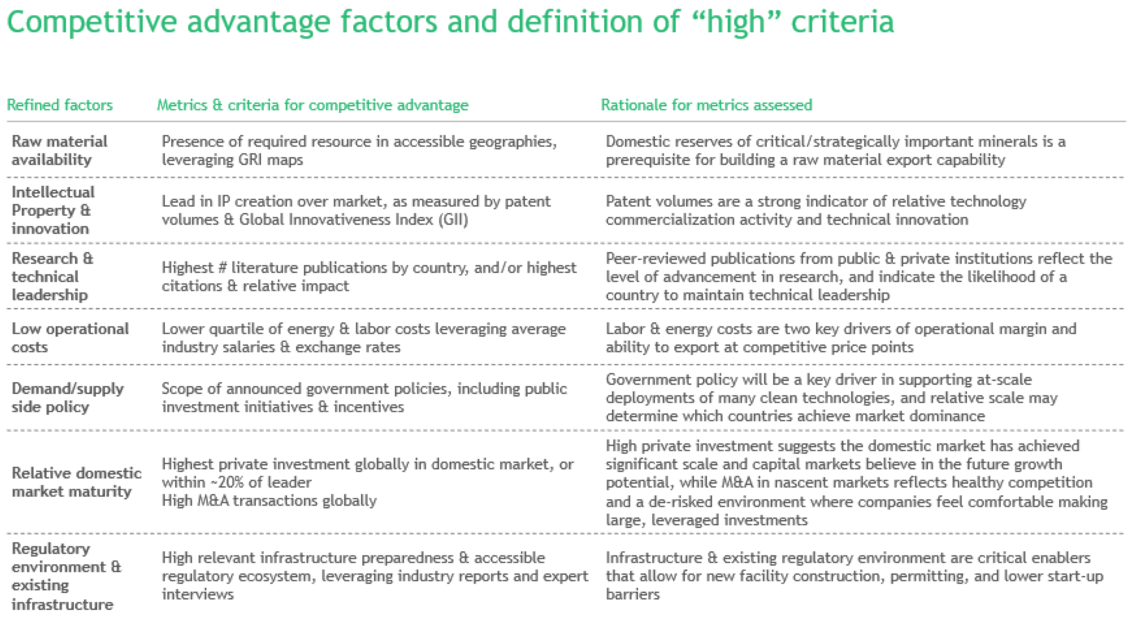


Definitions of competitive advantage ratings

Competitive advantage driver	High	Medium	Low
① **Existing environmental regulatory support**	**Direct financial support** (e.g., subsidies, carbon taxes)	**Indirect financial support** (e.g., tax breaks, tariffs, etc.)	**Non-financial support** (e.g., permitting, etc.)
② **Intellectual Property, technical expertise, and R&D availability**	Technology is **nascent** with **high potential and defensible IP**	Technology has **medium potential OR defensible IP**	Technology is **proven with existing patents in place**
③ **Providers / supplier concentration**	**Oligopoly** (Top five players control >60% of the market)	**Concentrated** (Top five players control 40-60% of the market)	**Fragmented** (Top five players control <40% of the market)
④ **Trained/skilled labor force availability**	**Highly specialized skills** needed (e.g., welding)	**General skilled labor** needed (e.g., electric wiring)	**Little skilled labor needed** (e.g., line plant operators)
⑤ **Cost advantage potential**	Inputs are **localized without a global market** (e.g., labor)	Inputs are **regionally-traded commodities** (e.g., nat. gas)	Inputs are **global commodities** (e.g., steel)
⑥ **Market ecosystem maturity**	**Robust global markets exist to connect buyers and sellers**	**Global or inter-regional markets are emerging**	**Existing markets are largely regional in nature**
⑦ **Relevant infrastructure potential**	**Existing infrastructure can be leveraged** (e.g., port export terminals)	**Existing infrastructure requires upgrades** (e.g., traditional O&G refineries)	**Fully new infrastructure is required** (e.g., CO_2 pipelines)
⑧ **Financing access**	**Markets do not provide financing** (e.g., govt. support is needed)	Financing is **costly or provided by niche investors** (e.g., VC)	Financing is **easily accessed through existing markets**
⑨ **Input material availability and concentration**	**Concentrated** (80% of market is owned by <5 countries)	**Fragmented** (80% of market is owned by 5-15 countries)	**Highly fragmented** (80% of market is owned by >15 countries)

Figure 10.3 – Definitions of Competitive Advantage Ratings

Following these initial market and competitive analyses, we prioritized a subset of value chain segments with strong market potential and capacity for the U.S. to develop a durable competitive advantage. For each of these prioritized segments, we performed a qualitative and quantitative evaluation that spanned the following seven dimensions:

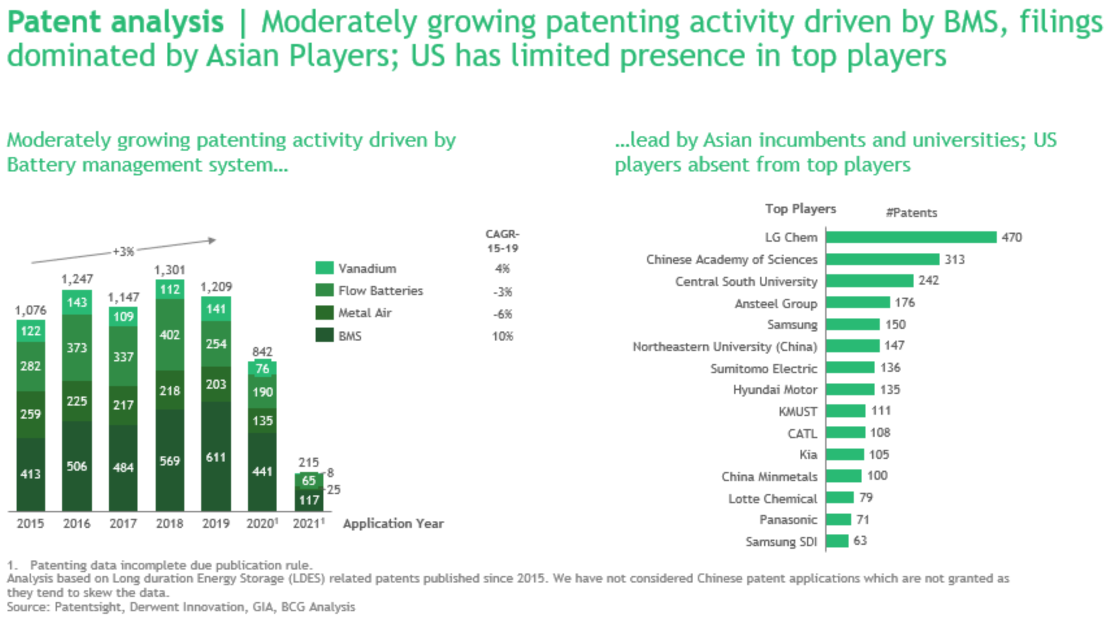


Competitive advantage factors and definition of "high" criteria

Refined factors	Metrics & criteria for competitive advantage	Rationale for metrics assessed
Raw material availability	Presence of required resource in accessible geographies, leveraging GRI maps	Domestic reserves of critical/strategically important minerals is a prerequisite for building a raw material export capability
Intellectual Property & innovation	Lead in IP creation over market, as measured by patent volumes & Global Innovativeness Index (GII)	Patent volumes are a strong indicator of relative technology commercialization activity and technical innovation
Research & technical leadership	Highest # literature publications by country, and/or highest citations & relative impact	Peer-reviewed publications from public & private institutions reflect the level of advancement in research, and indicate the likelihood of a country to maintain technical leadership
Low operational costs	Lower quartile of energy & labor costs leveraging average industry salaries & exchange rates	Labor & energy costs are two key drivers of operational margin and ability to export at competitive price points
Demand/supply side policy	Scope of announced government policies, including public investment initiatives & incentives	Government policy will be a key driver in supporting at-scale deployments of many clean technologies, and relative scale may determine which countries achieve market dominance
Relative domestic market maturity	Highest private investment globally in domestic market, or within ~20% of leader High M&A transactions globally	High private investment suggests the domestic market has achieved significant scale and capital markets believe in the future growth potential, while M&A in nascent markets reflects healthy competition and a de-risked environment where companies feel comfortable making large, leveraged investments
Regulatory environment & existing infrastructure	High relevant infrastructure preparedness & accessible regulatory ecosystem, leveraging industry reports and expert interviews	Infrastructure & existing regulatory environment are critical enablers that allow for new facility construction, permitting, and lower start-up barriers

Figure 10.4 – Competitive Advantage Factors and Definition of Criteria.

As a result of the analysis, competitive advantage factors were assigned a ranking of “high” or “low” using the above metrics to determine current U.S. competitiveness. A factor was considered a “key dimension” within a given value chain segment if it was a critical unlock, in that it enabled a country’s competitive participation in the segment. For example, competitiveness in project development for energy-intensive technologies (e.g., low-carbon H2, DAC) requires low renewable energy costs. Countries could then invest in this “key dimension” to build competitive advantage or, if possible, capitalize on their existing advantage.



Patent analysis | Moderately growing patenting activity driven by BMS, filings dominated by Asian Players; US has limited presence in top players

Moderately growing patenting activity driven by Battery management system...

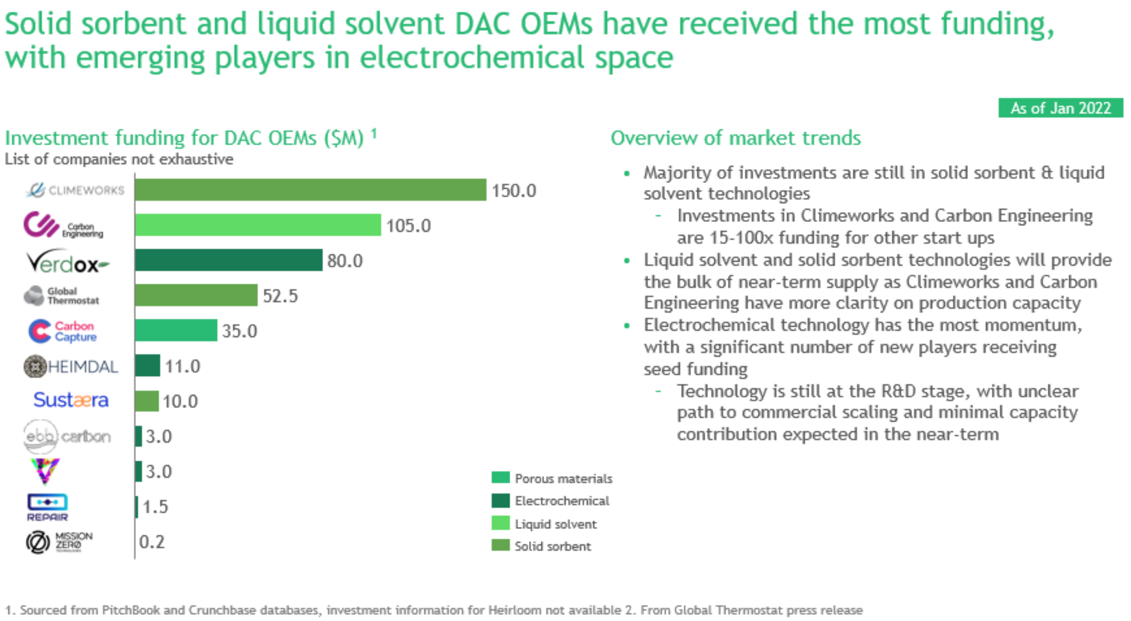
...lead by Asian incumbents and universities; US players absent from top players

1. Patenting data incomplete due publication rule.
Analysis based on Long duration Energy Storage (LDES) related patents published since 2015. We have not considered Chinese patent applications which are not granted as they tend to skew the data.
Source: Patentsight, Derwent Innovation, GIA, BCG Analysis

Figure 10.5 – Example Competitive Advantage Analysis Inputs

10.1.3 Socioeconomic impact

The third level of analysis focused on socioeconomic impact measured through job creation. Per prioritized value chain segment, we estimated the number of jobs created and assessed job quality (including duration, salary, and level of education required) using the process below:



Solid sorbent and liquid solvent DAC OEMs have received the most funding, with emerging players in electrochemical space

As of Jan 2022

Investment funding for DAC OEMs ($M) [1]

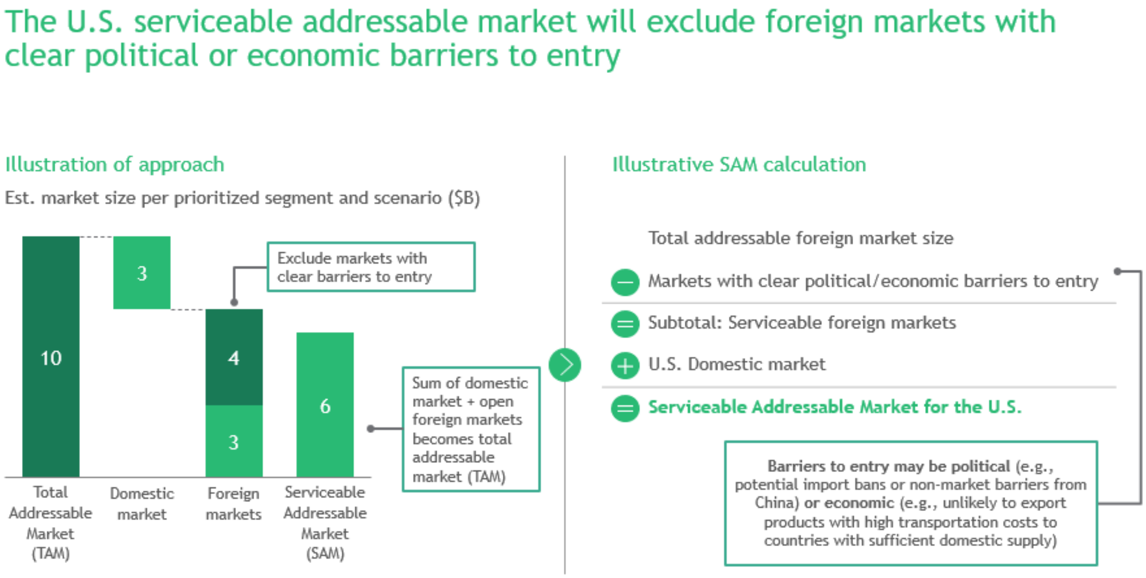
List of companies not exhaustive

Overview of market trends

- Majority of investments are still in solid sorbent & liquid solvent technologies
  - Investments in Climeworks and Carbon Engineering are 15-100x funding for other start ups
- Liquid solvent and solid sorbent technologies will provide the bulk of near-term supply as Climeworks and Carbon Engineering have more clarity on production capacity
- Electrochemical technology has the most momentum, with a significant number of new players receiving seed funding
  - Technology is still at the R&D stage, with unclear path to commercial scaling and minimal capacity contribution expected in the near-term

1. Sourced from PitchBook and Crunchbase databases, investment information for Heirloom not available 2. From Global Thermostat press release

Figure 10.6 – Example Competitive Advantage Analysis Inputs



The U.S. serviceable addressable market will exclude foreign markets with clear political or economic barriers to entry

Illustration of approach

Est. market size per prioritized segment and scenario ($B)

Exclude markets with clear barriers to entry

Sum of domestic market + open foreign markets becomes total addressable market (TAM)

Illustrative SAM calculation

Total addressable foreign market size

− Markets with clear political/economic barriers to entry

= Subtotal: Serviceable foreign markets

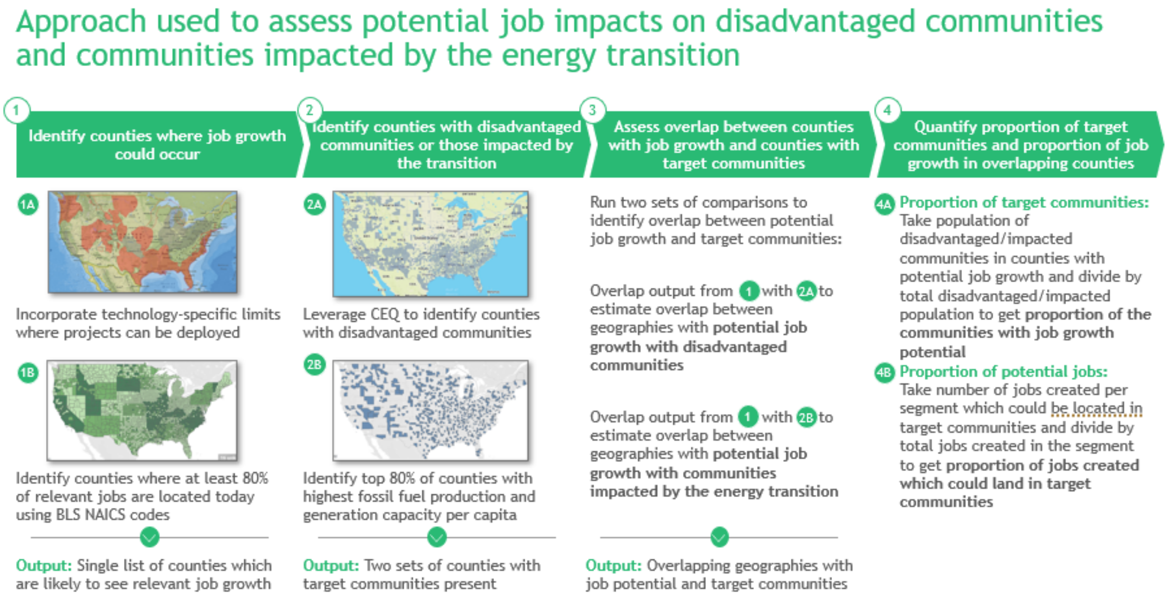
\+ U.S. Domestic market

= **Serviceable Addressable Market for the U.S.**

Barriers to entry may be political (e.g., potential import bans or non-market barriers from China) **or economic** (e.g., unlikely to export products with high transportation costs to countries with sufficient domestic supply)

Figure 10.7 – Approach to Calculating Job Growth by Education Level

Further, we assessed the potential job impact on disadvantaged communities and those impacted by the energy transition. We estimated the proportion of job growth expected in these communities under the status quo to represent a lower bound of job creation (i.e., if jobs created matched current geographic distribution of similar job types). Policy interventions could focus development of these technologies in regions that have more overlap with disadvantaged communities.



Approach used to assess potential job impacts on disadvantaged communities and communities impacted by the energy transition

1 Identify counties where job growth could occur

1A Incorporate technology-specific limits where projects can be deployed

1B Identify counties where at least 80% of relevant jobs are located today using BLS NAICS codes

Output: Single list of counties which are likely to see relevant job growth

2 Identify counties with disadvantaged communities or those impacted by the transition

2A Leverage CEQ to identify counties with disadvantaged communities

2B Identify top 80% of counties with highest fossil fuel production and generation capacity per capita

Output: Two sets of counties with target communities present

3 Assess overlap between counties with job growth and counties with target communities

Run two sets of comparisons to identify overlap between potential job growth and target communities:

Overlap output from 1 with 2A to estimate overlap between geographies with **potential job growth with disadvantaged communities**

Overlap output from 1 with 2B to estimate overlap between geographies with **potential job growth with communities impacted by the energy transition**

Output: Overlapping geographies with job potential and target communities

4 Quantify proportion of target communities and proportion of job growth in overlapping counties

4A **Proportion of target communities:** Take population of disadvantaged/impacted communities in counties with potential job growth and divide by total disadvantaged/impacted population to get **proportion of the communities with job growth potential**

4B **Proportion of potential jobs:** Take number of jobs created per segment which could be located in target communities and divide by total jobs created in the segment to get **proportion of jobs created which could land in target communities**

Figure 10.8 – Approach Used to Assess Potential Job Impacts

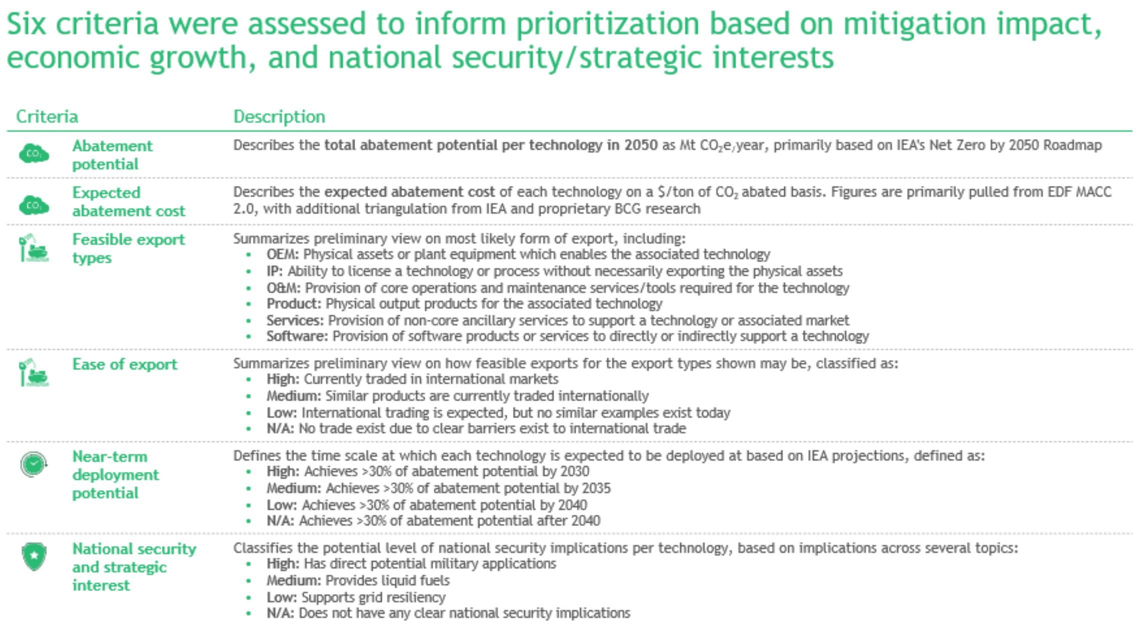
10.2 Selection of Technologies for Analysis

This analysis began by considering a long list of technology clusters that combined subsets of technologies with significant overlap in underlying value chains. Likewise, similar technologies with significant variations in the supply chain were split into separate clusters.

For example, offshore and onshore wind require key differences in permitting, siting, construction skill sets, and capital costs, and thus were considered separately. Blue and green hydrogen share a core value chain (including conversion, distribution, and storage), and thus were combined. Similarly, utility-scale and distributed-grid solar were considered separately due to variances in sourcing, installation, and operations.

From this list, our goal was to develop a balanced subset with promising carbon abatement potential and a strong fit in other dimensions – to ensure a holistic view across the technological, strategic, and economic landscape. Some highly mature technologies (such as traditional utility-scale solar and wind renewable electricity generation) were excluded because the U.S. is less likely to build a significant competitive advantage in developed markets that are less sensitive to policy and investment decisions.

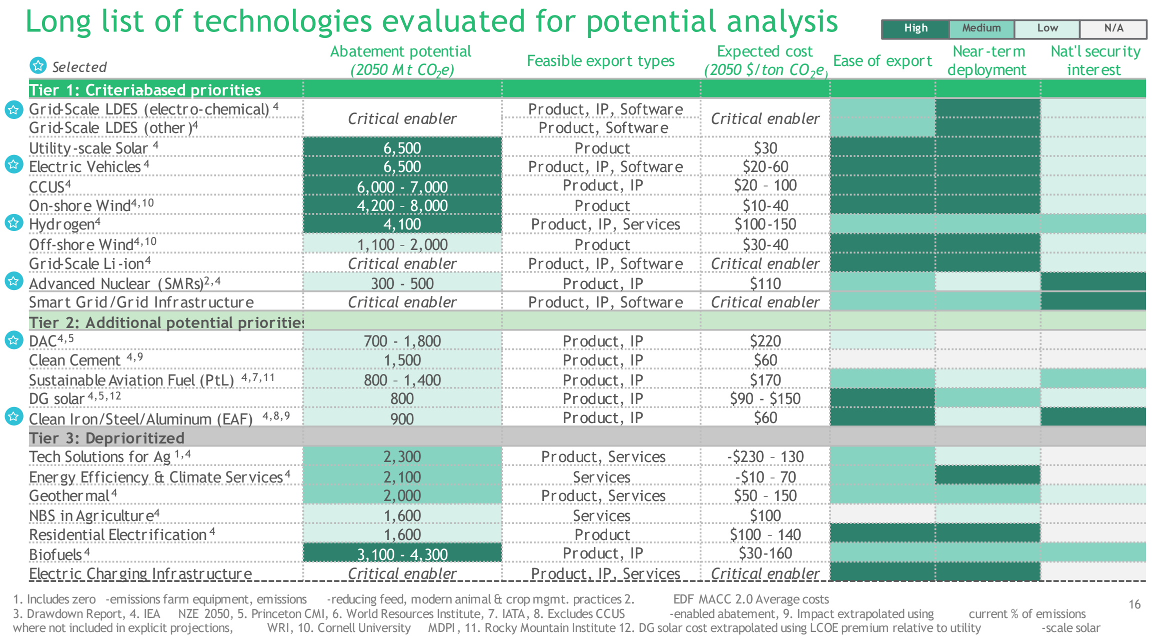
The Final criteria for the chosen technologies centered on six areas of assessment:



Six criteria were assessed to inform prioritization based on mitigation impact, economic growth, and national security/strategic interests

Criteria	Description
Abatement potential	Describes the **total abatement potential per technology in 2050** as Mt CO_2e/year, primarily based on IEA's Net Zero by 2050 Roadmap
Expected abatement cost	Describes the **expected abatement cost** of each technology on a \$/ton of CO_2 abated basis. Figures are primarily pulled from EDF MACC 2.0, with additional triangulation from IEA and proprietary BCG research
Feasible export types	Summarizes preliminary view on most likely form of export, including: • **OEM:** Physical assets or plant equipment which enables the associated technology • **IP:** Ability to license a technology or process without necessarily exporting the physical assets • **O&M:** Provision of core operations and maintenance services/tools required for the technology • **Product:** Physical output products for the associated technology • **Services:** Provision of non-core ancillary services to support a technology or associated market • **Software:** Provision of software products or services to directly or indirectly support a technology
Ease of export	Summarizes preliminary view on how feasible exports for the export types shown may be, classified as: • **High:** Currently traded in international markets • **Medium:** Similar products are currently traded internationally • **Low:** International trading is expected, but no similar examples exist today • **N/A:** No trade exist due to clear barriers exist to international trade
Near-term deployment potential	Defines the time scale at which each technology is expected to be deployed at based on IEA projections, defined as: • **High:** Achieves >30% of abatement potential by 2030 • **Medium:** Achieves >30% of abatement potential by 2035 • **Low:** Achieves >30% of abatement potential by 2040 • **N/A:** Achieves >30% of abatement potential after 2040
National security and strategic interest	Classifies the potential level of national security implications per technology, based on implications across several topics: • **High:** Has direct potential military applications • **Medium:** Provides liquid fuels • **Low:** Supports grid resiliency • **N/A:** Does not have any clear national security implications

Figure 10.9 – Criteria for Technology Assessment



Long list of technologies evaluated for potential analysis

High | Medium | Low | N/A

☆ *Selected*

	Abatement potential *(2050 Mt CO_2e)*	Feasible export types	Expected cost *(2050 \$/ton CO_2e)*	Ease of export	Near-term deployment	Nat'l security interest
Tier 1: Criteriabased priorities						
☆ Grid-Scale LDES (electro-chemical) ^{4}	*Critical enabler*	Product, IP, Software	*Critical enabler*	Medium	High	Low
Grid-Scale LDES (other)^{4}		Product, Software		Medium	High	Low
Utility-scale Solar ^{4}	6,500	Product	\$30	High	High	Low
☆ Electric Vehicles ^{4}	6,500	Product, IP, Software	\$20-60	High	High	Low
CCUS^{4}	6,000 - 7,000	Product, IP	\$20 - 100	High	High	Low
On-shore Wind^{4,10}	4,200 - 8,000	Product	\$10-40	High	High	Low
☆ Hydrogen^{4}	4,100	Product, IP, Services	\$100-150	Medium	Medium	Medium
Off-shore Wind^{4,10}	1,100 - 2,000	Product	\$30-40	High	High	Low
Grid-Scale Li-ion^{4}	*Critical enabler*	Product, IP, Software	*Critical enabler*	High	High	Low
☆ Advanced Nuclear (SMRs)^{2,4}	300 - 500	Product, IP	\$110	Medium	Low	High
Smart Grid/Grid Infrastructure	*Critical enabler*	Product, IP, Software	*Critical enabler*	Medium	Medium	High
Tier 2: Additional potential prioritie						
☆ DAC^{4,5}	700 - 1,800	Product, IP	\$220	Low	N/A	N/A
Clean Cement ^{4,9}	1,500	Product, IP	\$60	N/A	N/A	N/A
Sustainable Aviation Fuel (PtL) ^{4,7,11}	800 - 1,400	Product, IP	\$170	Medium	Low	Medium
DG solar ^{4,5,12}	800	Product, IP	\$90 - \$150	High	Medium	Low
☆ Clean Iron/Steel/Aluminum (EAF) ^{4,8,9}	900	Product, IP	\$60	High	Low	High
Tier 3: Deprioritized						
Tech Solutions for Ag ^{1,4}	2,300	Product, Services	-\$230 - 130	Medium	Low	N/A
Energy Efficiency & Climate Services^{4}	2,100	Services	-\$10 - 70	Medium	High	N/A
Geothermal^{4}	2,000	Product, Services	\$50 - 150	Medium	Medium	Low
NBS in Agriculture^{4}	1,600	Services	\$100	N/A	N/A	N/A
Residential Electrification^{4}	1,600	Product	\$100 - 140	High	High	N/A
Biofuels^{4}	3,100 - 4,300	Product, IP	\$30-160	Medium	Medium	Medium
Electric Charging Infrastructure	*Critical enabler*	Product, IP, Services	*Critical enabler*	High	High	N/A

1. Includes zero -emissions farm equipment, emissions -reducing feed, modern animal & crop mgmt. practices 2. EDF MACC 2.0 Average costs 3. Drawdown Report, 4. IEA NZE 2050, 5. Princeton CMI, 6. World Resources Institute, 7. IATA, 8. Excludes CCUS -enabled abatement, 9. Impact extrapolated using current % of emissions where not included in explicit projections, WRI, 10. Cornell University MDPI, 11. Rocky Mountain Institute 12. DG solar cost extrapolated using LCOE premium relative to utility -scale solar

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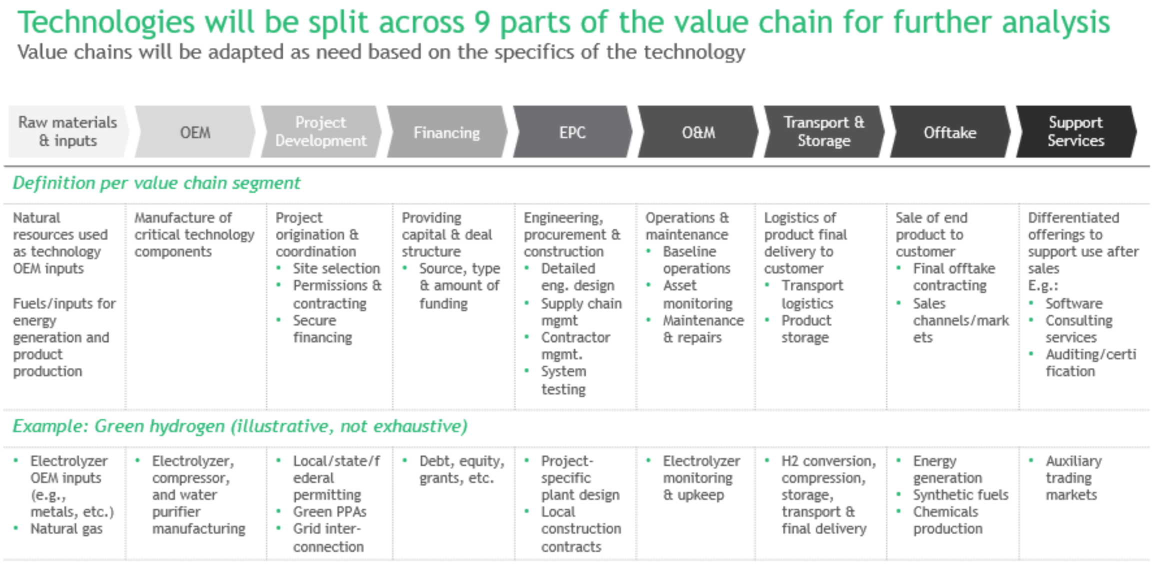
Figure 10.10 –Technologies Prioritized in this Analysis

While this report focuses on these six technologies, it does not discount the need for a broad set of solutions across industries to drive successful decarbonization, support a just energy transition, and secure the U.S. position in a future green economy (e.g., traditional renewables, electrification, energy efficiency).

Analysis at Value Chain Segment level

The six technologies above were further broken down into specific value chain segments. This breakdown enabled a focused assessment at each stage within a technology, including more granular market analyses, jobs and economic impact projections, and assessments of the U.S. competitive advantage in each of these areas.

Value chain segments for analysis across technologies reflected this standardized list of critical segments, with some modifications across technologies:



Technologies will be split across 9 parts of the value chain for further analysis

Value chains will be adapted as need based on the specifics of the technology

Raw materials & inputs	OEM	Project Development	Financing	EPC	O&M	Transport & Storage	Offtake	Support Services
Definition per value chain segment								
Natural resources used as technology OEM inputs Fuels/inputs for energy generation and product production	Manufacture of critical technology components	Project origination & coordination • Site selection • Permissions & contracting • Secure financing	Providing capital & deal structure • Source, type & amount of funding	Engineering, procurement & construction • Detailed eng. design • Supply chain mgmt • Contractor mgmt. • System testing	Operations & maintenance • Baseline operations • Asset monitoring • Maintenance & repairs	Logistics of product final delivery to customer • Transport logistics • Product storage	Sale of end product to customer • Final offtake contracting • Sales channels/markets	Differentiated offerings to support use after sales E.g.: • Software • Consulting services • Auditing/certification
Example: Green hydrogen (illustrative, not exhaustive)								
• Electrolyzer OEM inputs (e.g., metals, etc.) • Natural gas	• Electrolyzer, compressor, and water purifier manufacturing	• Local/state/federal permitting • Green PPAs • Grid inter-connection	• Debt, equity, grants, etc.	• Project-specific plant design • Local construction contracts	• Electrolyzer monitoring & upkeep	• H2 conversion, compression, storage, transport & final delivery	• Energy generation • Synthetic fuels • Chemicals production	• Auxiliary trading markets

Figure 10.11 – Segment-level Value Chain Analysis

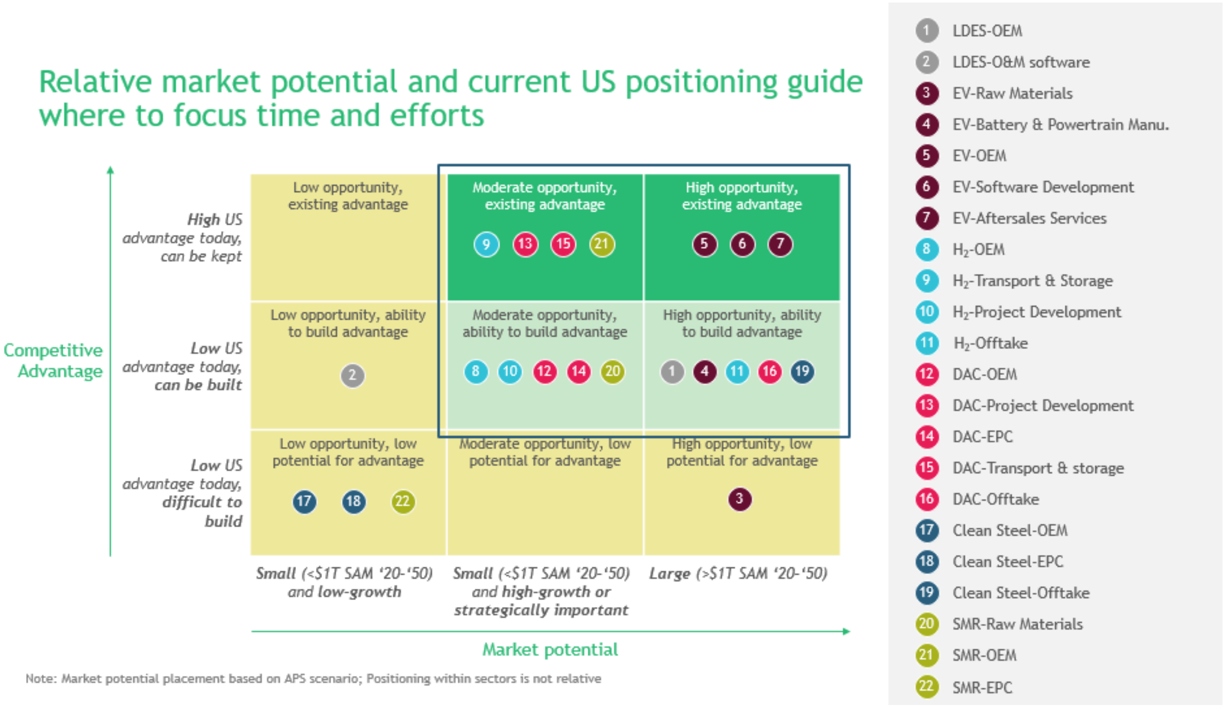


Figure 10.12 – U.S. Current Positioning and Relative Market Potential

10.3 Implications

Value chain segments were assessed and grouped on a 3x3 matrix based on U.S. potential for competitive advantage and market potential, as shown in Figure 10.12. Along the y-axis, segments are divided by high vs. low existing U.S. competitive advantage: Placing high on this axis means a segment has strong competitive advantage that can be maintained, while being in the medium range implies a low competitive advantage, but with potential to build.

Similarly, along the x-axis, the market size and growth potential are divided into large (>$1T) vs. small market size. Placing further right along this axis signifies that a segment has a large market size, while the middle is for segments with small market size, but high-growth potential or strategic importance.

11 Summary and next steps

An in-depth analysis at the value chain segment level for six emerging clean technologies has found the U.S. is well positioned to compete in specific value chain segments for each technology. Using estimated market potential through 2050 and an assessment of the U.S.'s current competitive positioning in a subset of priority segments, included in the green boxes of the matrix below, we identified policy changes and investments to maintain or build durable competitive advantage.

Actions to enable competitive advantage in these specific segments were identified, broadly falling across six primary categories using both pull from demand and push from supply:

- *Demand pull:* Enhance competitiveness by driving costs down the learning curve through increased technology demand and deployment
    - **Decrease green premiums:** Increase demand by either reducing the cost of the technology or increasing the cost of emitting alternatives
    - **Increase volumes deployed:** Increase total technology deployment through direct procurements or deployment targets
    - **Ensure access to export markets:** Increase demand for domestic companies' exports by clearing non-tariff barriers

- *Supply push:* Boost competitiveness by building economies of scale through investment in manufacturing and maintaining lead in product quality through R&D
    - **Streamline deployment:** Reduce barriers to deployment to de-risk investment in projects, increasing number of projects deployed and driving costs down the learning curve
    - **De-risk project and infrastructure investment:** Increase access to capital for relevant projects/infrastructure, decreasing technology costs
    - **Maintain lead in quality/cost through innovation:** Promote R&D to maintain technological competitiveness in product quality and/or cost

It is important to note that this study was conducted at a single point in time with a snapshot of limited forward-looking data. As new forecasts emerge and both the competitive landscape and technology options shift, it will be important to reevaluate the conclusions expressed here.

Next steps: Building U.S. competitive advantage will require translating this analysis into action. That means formulating specific policy proposals and working with relevant stakeholders to build support for implementation. Through well-crafted policy and stakeholder support, the U.S. has opportunity to become a dominant player in the emerging technologies needed to avert the worst impacts of climate change.

We hope this work can be used as a framework to assess additional emerging clean technologies in the future. Although this assessment was purely focused on six specific technologies, the approach and methodology could be applied to provide a comparative view across a broader set of other potential technologies -- which may include CCUS, clean cement, sustainable aviation fuel, or utility-scale renewables.

The implications of this study are clear: The U.S. has the potential to seize and maintain a competitive advantage in several clean energy industries, given the right mixture of government, investment, and industry support.

12 About the Authors

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14 Acronyms / Glossary

ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
APS	Announced pledges scenario
ARDP	Advanced Reactor Demonstration Program
AV	Autonomous Vehicle
BF-BOF	Blast furnace-basic oxygen furnace
CapEx	Capital expenses
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon capture, utilization, and storage
CO_2	Carbon dioxide
DAC	Direct air capture
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DPA	Defense Production Act
DRI	Direct reduction of ion
EAF	Electric arc furnace
EOL	End of Life
EPC	Engineering, Procurement, and Construction
EPD	Environmental Product Declarations
EU	European Union
EV	Electric vehicle
EXIM	Export Import Bank
Gt	Gigaton
GW	Gigawatt
H_2	Hydrogen
HALEU	High-assay low enriched uranium
HTGR	High Temperature Gas-cooled Reactor
ICE	Internal combustion vehicle
IEA	International Energy Agency
IIJA	Infrastructure Investment and Jobs Act
IP	Intellectual Property
IPHE	International Partnership for Hydrogen Fuel Cells and the Economy
IRP	Integrated Resource Plan
kW	Kilowatt
LCA	Lifecycle analysis
LDES	Long duration energy storage
LDES	Long Duration Energy Storage
LOHC	Liquid organic hydrogen carrier
LPO	Loan Program Office
LWR	Light Water Reactor
Margin pool	Gross profit, gross profit margin multiplied by total market size
ML	Machine Learning
MOE	Molten oxide electrolysis
MSR	Molten Salt Reactor
MW	Megawatt
NEV	Neighborhood Electric Vehicle
NNSA	National Nuclear Security Administration
NRC	Nuclear Regulatory Commission
NZE	Net-zero emissions scenario

O_2	Oxygen
OEM	Original equipment manufacturer
OpEx	Operating expenses
PPA	Power purchase agreement
RE	Renewable energy
SAM	Serviceable addressable market
SFR	Sodium Fast Reactor
SMR	Small modular reactor (advanced nuclear)
SOM	Serviceable obtainable market
STEPS	Stated policies scenario
TAM	Total addressable market
USPS	U.S. Postal Service

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