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Potential for US Competitiveness in Emerging Clean Technologies

Publication Appendix

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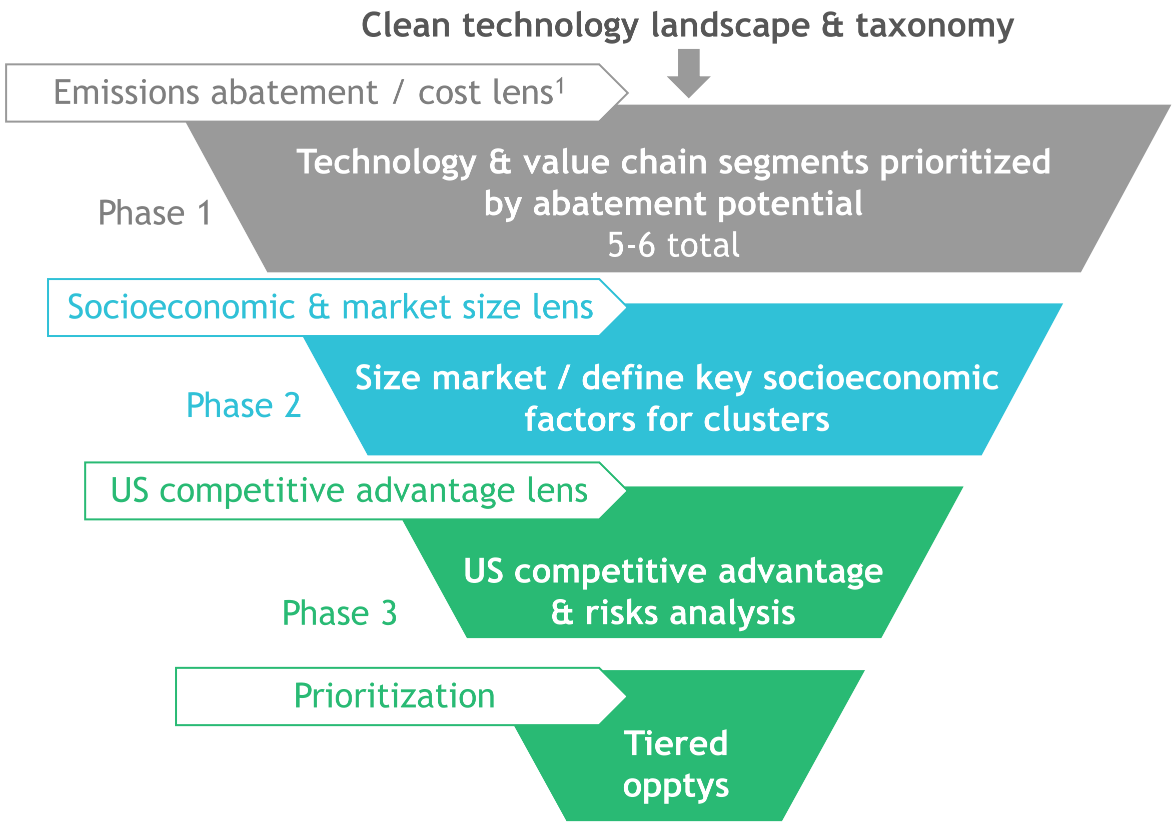
Context and approach

Context | 3-phase approach to prioritize technologies based on abatement potential, socioeconomic factors, and US competitive advantage



Clean technology landscape & taxonomy

Emissions abatement / cost lens[1]

Phase 1

Technology & value chain segments prioritized by abatement potential
5-6 total

Socioeconomic & market size lens

Phase 2

Size market / define key socioeconomic factors for clusters

US competitive advantage lens

Phase 3

US competitive advantage & risks analysis

Prioritization

Tiered opptys

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1. Assessed per technology spanning the full value chain

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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

Definition per value chain segment

Raw materials & inputs	OEM	Project Development	Financing	EPC	O&M	Transport & Storage	Offtake	Support Services
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)

Raw materials & inputs	OEM	Project Development	Financing	EPC	O&M	Transport & Storage	Offtake	Support Services
• 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

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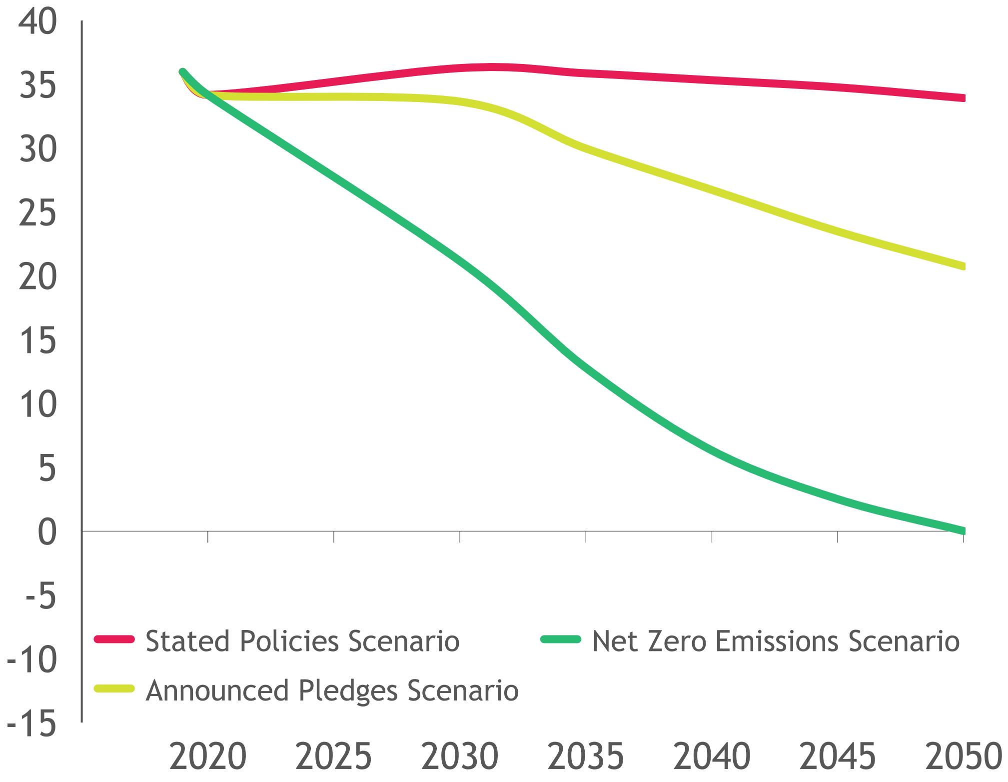
Scenarios built on data from IEA World Energy Outlook deployment forecasts

Annual CO2 Emissions (GTPA)



Est. 2050 impact (C°)

1.8 – 2.1°
(STEPS)

1.7 - 2.0°
(APS)

1.4 - 1.7°
(NZE)

Scenario descriptions

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

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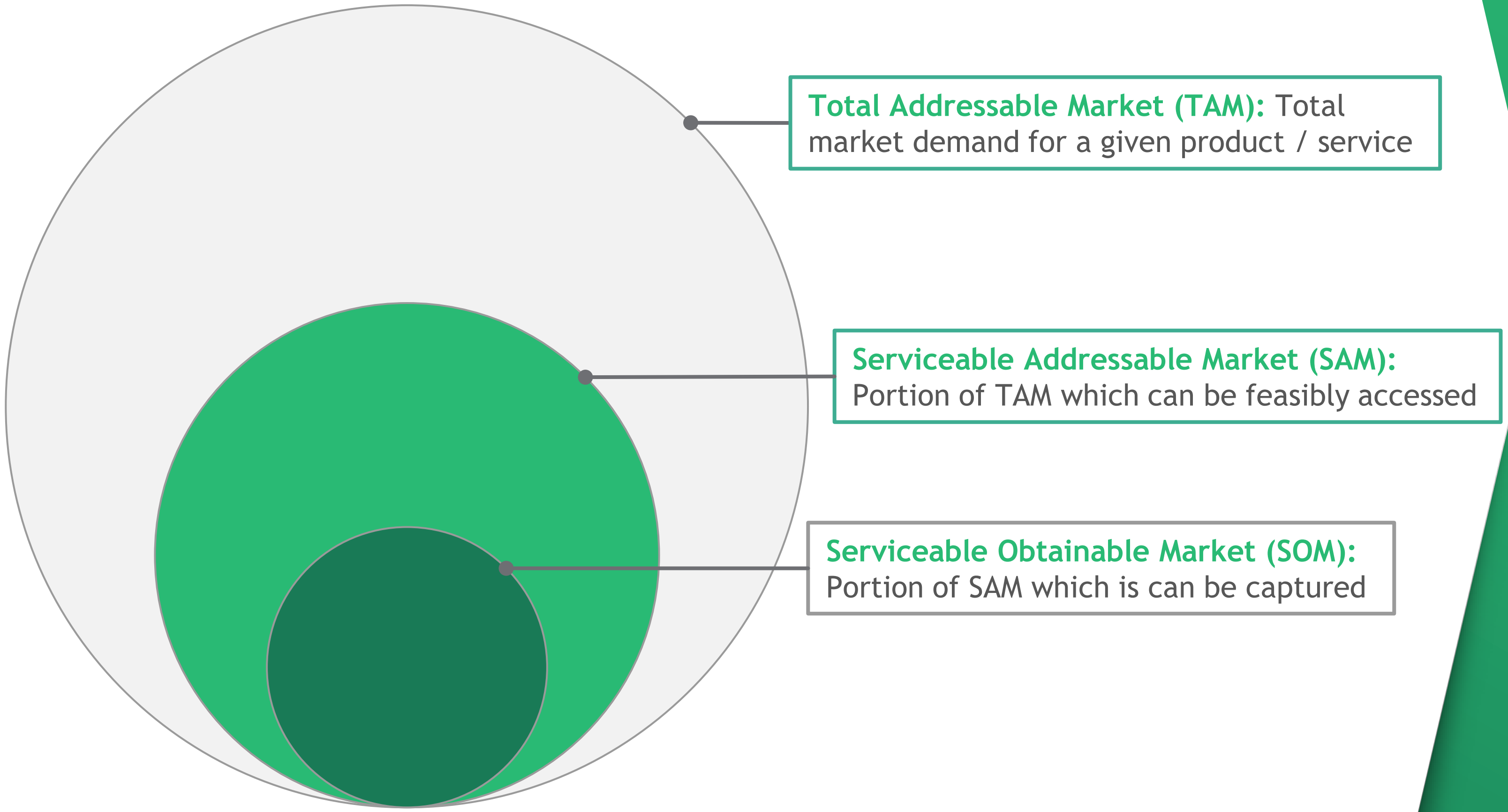
Market sizing completed at three levels



Total Addressable Market (TAM): Total market demand for a given product / service

Serviceable Addressable Market (SAM): Portion of TAM which can be feasibly accessed

Serviceable Obtainable Market (SOM): Portion of SAM which is can be captured

SOM estimates leverage technology specific approaches using analogous examples

More detail on approach included on next slide

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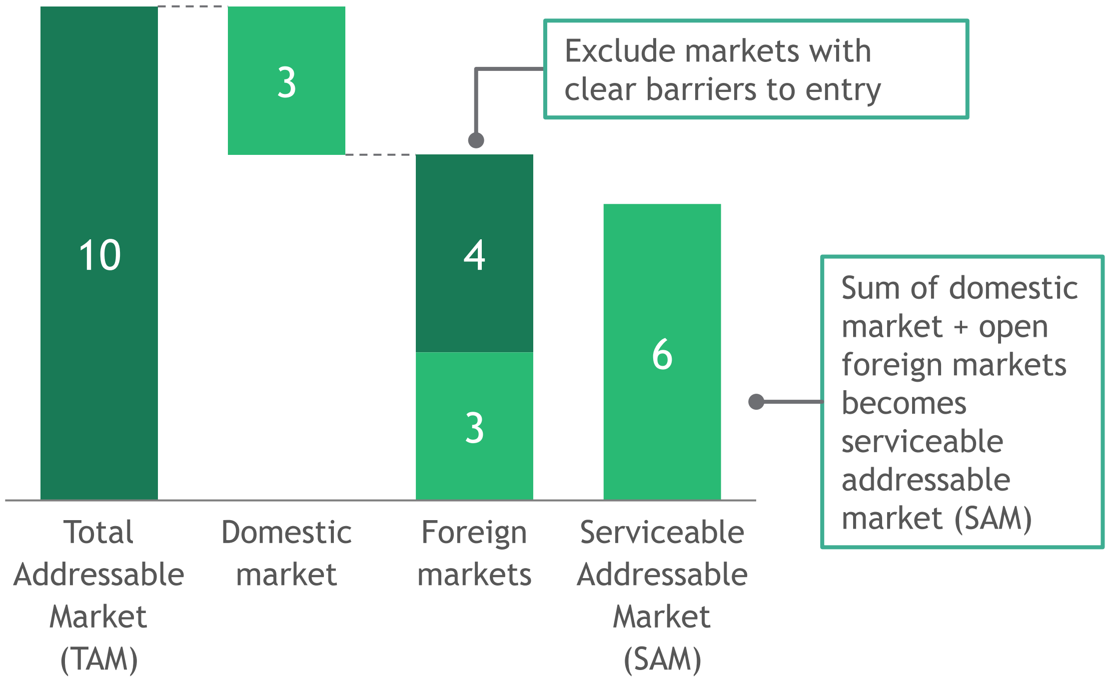
The U.S. serviceable addressable market will exclude foreign markets with clear political or economic barriers to entry

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 serviceable addressable market (SAM)

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 (SAM) 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)

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Backup | TAM exclusions approach is based on direct policy barriers, indirect policy barriers, and economic barriers

Trade policy barriers

Existing domestic or foreign trade policies with would directly or indirectly inhibit export of specific technology value chain segments

Trade barriers can include:

- U.S. export controls (e.g., dual-use controls)
- Bans on foreign investment
- Active embargoes or sanctions
- Significant domestic subsidies / state support for domestic industry

Ex: Trade barriers to advanced nuclear exports to China

- Raw materials: U.S. has prohibited export of raw materials to Chinese state-owned nuclear companies due to dual-use concerns
- OEM: U.S. has prohibited export of any advanced nuclear technologies to China due to dual-use concerns

Economic barriers

General observed or expected economic trends which would significantly hamper economic competitiveness of U.S. exports

Economic barriers can include:

- Prohibitively high transport costs
- Abundant / cheap domestic inputs
- Significant early lead in domestic IP

Ex: Economic barriers to clean steel offtake in the Asia-Pacific region

- Steel is extremely heavy, making shipping very expensive and limiting potential export destinations
- Large supply of cheap Chinese steel discourages other imports into Asia due to lack of cost-competitiveness

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U.S. SOM has been estimated by using current-state proxies within relevant markets for potential future-state market share

Technology	SOM % share of TAM	Reasoning
Clean Steel	5 – 15%	• Business as usual: Average U.S. share of global steel production, 2015-2020 • Market leader position: Servicing entirety of NA market, 2021 market size
Electric Vehicles	10 – 55% *Varies by segment*	• Business as usual: U.S. share of global EV vehicle production, 2021 • Market leader position: Chinese share of passenger vehicle production (raw materials, battery & powertrain manufacturing, OEM), U.S. share of global SaaS market (software, aftersales services)
Hydrogen	15 – 25%	• Business as usual: US share of global hydrogen production 2014-2018; DOE • Market leader position: Chinese share of global H2 2022
LDES	10 – 50%	• Business as usual: U.S. share of global Li-ion storage manufacturing capacity • Market leader position: China's projected share of global Li-ion manufacturing capacity in 2023
DAC	15 – 25%	• Business as usual: Based on US share of global hydrogen production 2014-2018 as proxy; DOE • Market leader position: Based on Chinese share of global H2 in 2022 as proxy; DOE
Advanced Nuclear SMRs	20 – 30%	• Business as usual: Share of all nuclear plants designed by U.S. companies • Market leader position: Share of ongoing nuclear plant projects designed by Chinese companies

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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

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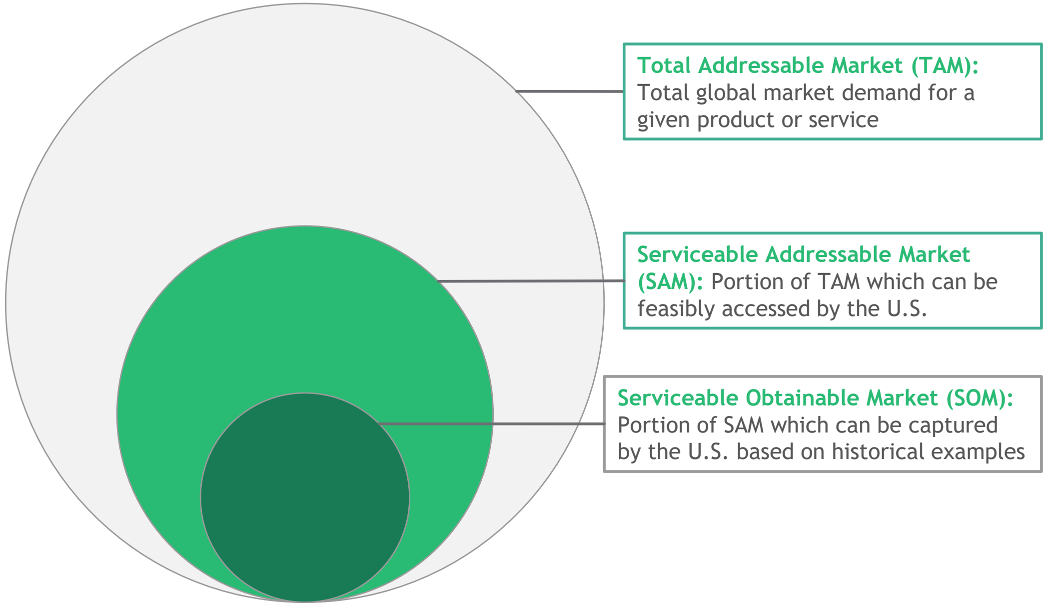
Context | Job numbers are conservatively based on Serviceable Obtainable Market (SOM), the lower bound estimate of potential U.S. global market share

Review of market size definitions used



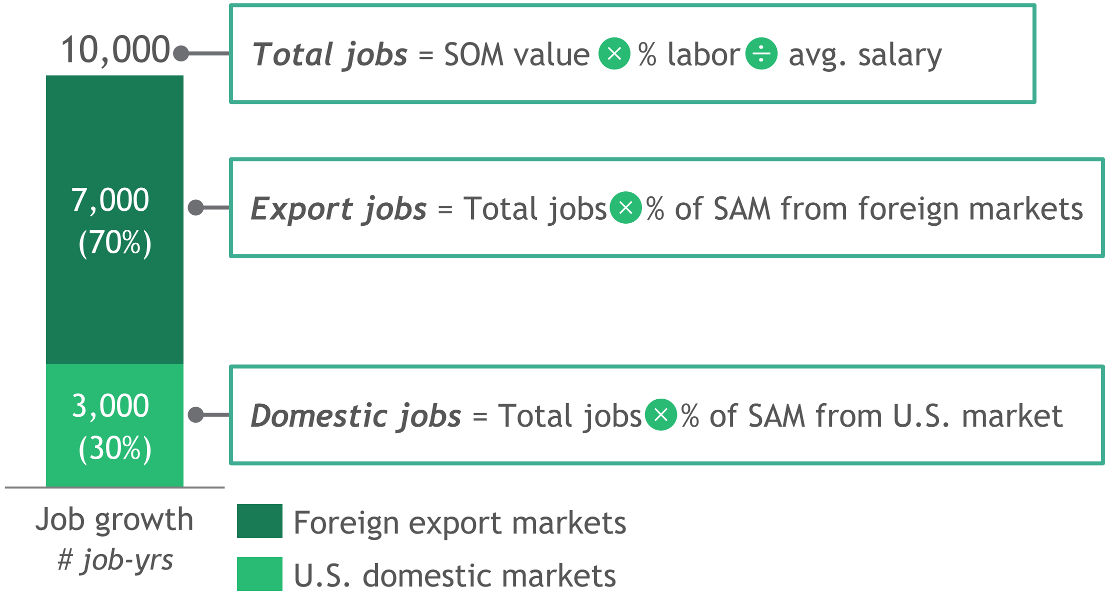
Total Addressable Market (TAM): Total global market demand for a given product or service

Serviceable Addressable Market (SAM): Portion of TAM which can be feasibly accessed by the U.S.

Serviceable Obtainable Market (SOM): Portion of SAM which can be captured by the U.S. based on historical examples

SOM is a conservative view of U.S. market potential which may be further increased with strategic policy support

Proposed approach to jobs quantification



Total jobs = SOM value × % labor ÷ avg. salary

Export jobs = Total jobs × % of SAM from foreign markets

Domestic jobs = Total jobs × % of SAM from U.S. market

Approach will likely overstate export-driven jobs and understate jobs created by the domestic market

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Context | Definition and example of job-years

What are job-years?

- A "job-year" is a measure of employment based on the equivalent of employing a single FTE (full-time equivalent) for one year
- Job-years = # of jobs x duration of jobs

Why use job-years?

- Unlike using the absolute number of jobs, job-years capture both the number of new jobs created as well as how long a given job would be expected to last
- Job-years can be thought of as the total amount of employment a given segment would create over time

Illustrative example of job years vs number of jobs:

Construction: 15 new construction jobs which last 2 years each

- 15 jobs x 2 years per job = **30 job-years**

O&M: 3 new maintenance jobs which last 10 years each

- 3 jobs x 10 years per job = **30 job-years**

Despite construction seeming to have more **jobs**, it is equivalent to O&M in terms of total **job-years**

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Deep dive | 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**

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Technology selection

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

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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: Criteria-based 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 priorities						
☆ 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	Low	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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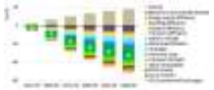
Backup | Sources for Carbon Abatement Potential

Key sources		Description
	**IEA (Net Zero Energy 2050 Report & others)**	Key emissions milestones required by sector, including carbon abatement targets
	**Princeton CMI**	Reviews technologies & scale required to achieve Net Zero emissions
	**EDF MACC 2.0**	Carbon abatement impact by clean technology through 2050, including abatement costs
	**World Resources Institute**	Historical view of carbon emissions by sector
	**IPCC**	Reviews technologies & scale required to achieve <1.5 degrees warming
	**Drawdown Report**	Granular view of carbon abatement impact of highly specific initiatives across industries and emissions sectors
Others sources include: IATA, NREL, Cornell MDPI, SEIA, RMI, LDES Society, International Geothermal Ass.		Industry group reports or technology-specific research studies

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Backup | Descriptions of potential export types

Export types	Description	Examples
OEM	The physical assets or plant equipment which enables the associated technology	• Li-ion battery pack • Wind turbines / solar panels
Intellectual Property (IP)	The ability to license a technology or process without necessarily exporting the physical associated assets	• Direct Air Capture (DAC) technology • Hydrogen electrolysis technology • Clean cement production processes
Operations & Maintenance (O&M)	The provision of core operations and maintenance services or tools required to deploy the associated technology	• Contracting specialized vessels to maintain offshore wind farms • Contracting to operate and maintain large CCUS plants
Product	The physical output products for the associated technology	• Clean steel products • Clean hydrogen / ammonia • Barrels of sustainable aviation fuel
Services	The provision of non-core ancillary services to support a specific technology or associated market	• Geothermal seismic studies to assess resource potential for future projects
Software	The provision of software products or services to support the operations of a technology, either directly or indirectly	• Battery operations software which help maximize project economics • EV charging software to optimize charging and provide load-balancing grid services

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Summary findings

Prioritized segments have been separated into three categories to inform Phase 3 recommendations

"Maintain U.S. leadership"

Current positioning:

- U.S. holds **existing advantage** in a **large market-potential segment**

Potential implication:

- Policymakers must be vigilant and aware of foreign competitors investing in the market and eroding competitive advantage
- Protective policies that invest in the future development pipeline, support existing players, and expand export potential can secure future U.S. positioning

"Invest to build advantage"

Current positioning:

- U.S. has **no advantage** in a **large market-potential segment**, but has the potential to build one

Potential implication:

- Significant, course-correcting public investment is required to build new U.S. advantage in a high-potential market segment
- Strong regulatory policy and large-scale demand- and supply-side public subsidies are likely advisable to leverage U.S. potential and capture market share

"Maintain status quo"

Current positioning:

- **Market potential is small** or U.S. has **no potential to build advantage**

Potential implication:

- Passive policy to create general environmental & regulatory structures that support innovation in the segment may be advisable
- Given low reward/high risk potential, no large-scale investments or structural reforms are advantageous

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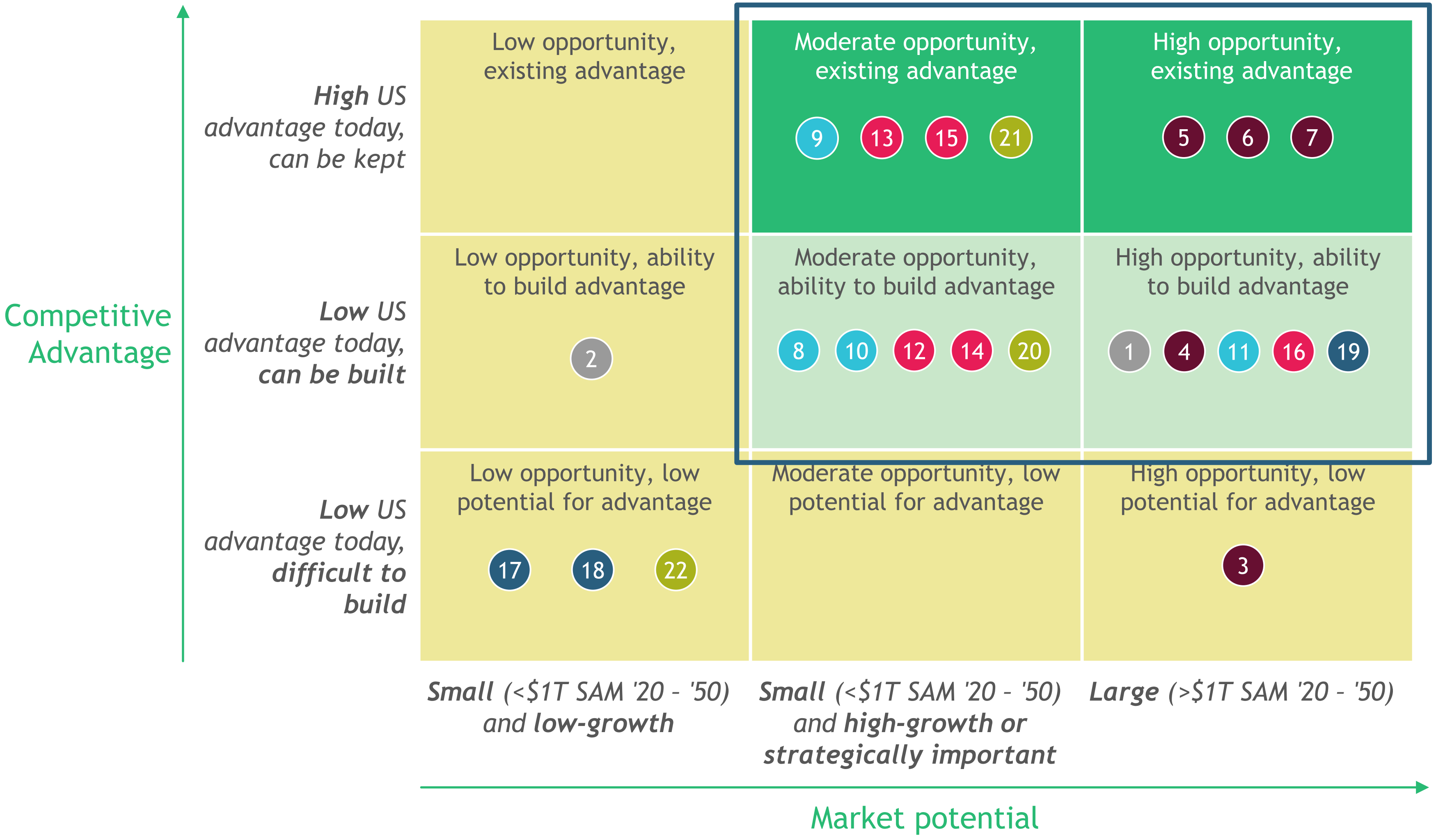
Relative market potential and current US positioning guide where to focus time and efforts



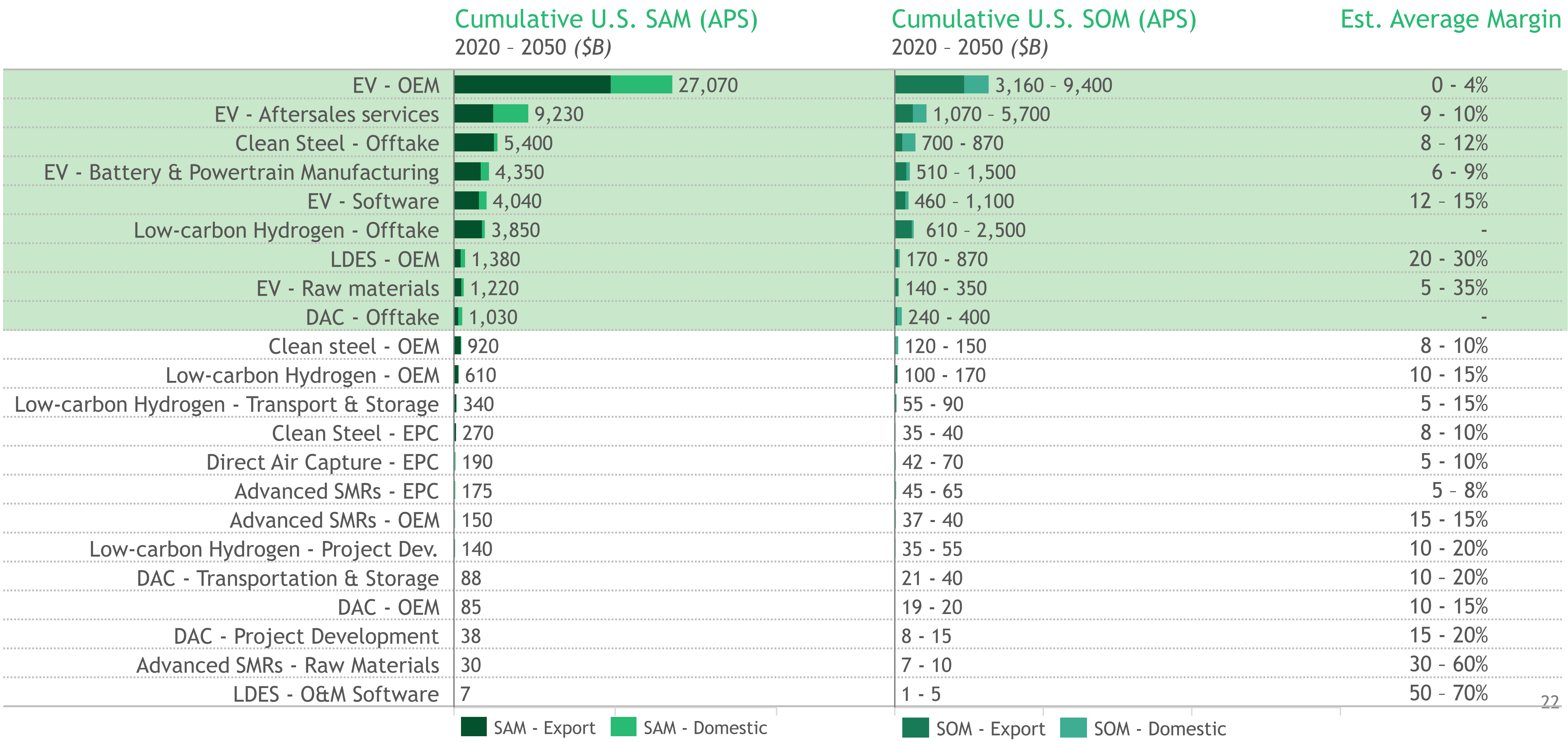
Competitive Advantage	***Small** (<$1T SAM '20 - '50) and **low-growth***	***Small** (<$1T SAM '20 - '50) and **high-growth or strategically important***	***Large** (>$1T SAM '20 - '50)*
***High** US advantage today, can be kept*	Low opportunity, existing advantage	Moderate opportunity, existing advantage 9 13 15 21	High opportunity, existing advantage 5 6 7
Low** US advantage today, **can be built	Low opportunity, ability to build advantage 2	Moderate opportunity, ability to build advantage 8 10 12 14 20	High opportunity, ability to build advantage 1 4 11 16 19
Low** US advantage today, **difficult to build	Low opportunity, low potential for advantage 17 18 22	Moderate opportunity, low potential for advantage	High opportunity, low potential for advantage 3

Market potential

Note: Market potential placement based on APS scenario; Positioning within sectors is not relative

1	LDES - OEM
2	LDES - O&M software
3	EV - Raw Materials
4	EV - Battery & Powertrain Manu.
5	EV - OEM
6	EV - Software Development
7	EV - Aftersales Services
8	H_2 - OEM
9	H_2 - Transport & Storage
10	H_2 - Project Development
11	H_2 - Offtake
12	DAC - OEM
13	DAC - Project Development
14	DAC - EPC
15	DAC - Transport & storage
16	DAC - Offtake
17	Clean Steel - OEM
18	Clean Steel - EPC
19	Clean Steel - Offtake
20	SMR - Raw Materials
21	SMR - OEM
22	SMR - EPC

Market sizing | EV value chain segments are largest across technologies in terms of market value, followed by select LDES and DAC segments



	Cumulative U.S. SAM (APS) 2020 – 2050 *($B)*	Cumulative U.S. SOM (APS) 2020 – 2050 *($B)*	Est. Average Margin
EV - OEM	27,070	3,160 – 9,400	0 - 4%
EV - Aftersales services	9,230	1,070 – 5,700	9 - 10%
Clean Steel - Offtake	5,400	700 - 870	8 - 12%
EV - Battery & Powertrain Manufacturing	4,350	510 - 1,500	6 - 9%
EV - Software	4,040	460 - 1,100	12 - 15%
Low-carbon Hydrogen - Offtake	3,850	610 - 2,500	-
LDES - OEM	1,380	170 - 870	20 - 30%
EV - Raw materials	1,220	140 - 350	5 - 35%
DAC - Offtake	1,030	240 - 400	-
Clean steel - OEM	920	120 - 150	8 - 10%
Low-carbon Hydrogen - OEM	610	100 - 170	10 - 15%
Low-carbon Hydrogen - Transport & Storage	340	55 - 90	5 - 15%
Clean Steel - EPC	270	35 - 40	8 - 10%
Direct Air Capture - EPC	190	42 - 70	5 - 10%
Advanced SMRs - EPC	175	45 - 65	5 – 8%
Advanced SMRs - OEM	150	37 - 40	15 - 15%
Low-carbon Hydrogen - Project Dev.	140	35 - 55	10 - 20%
DAC - Transportation & Storage	88	21 - 40	10 - 20%
DAC - OEM	85	19 - 20	10 - 15%
DAC - Project Development	38	8 - 15	15 - 20%
Advanced SMRs - Raw Materials	30	7 - 10	30 - 60%
LDES - O&M Software	7	1 - 5	50 - 70%

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Competitive advantage | Overlap between grey "key dimensions" and areas where U.S. holds advantage suggests strong domestic position today

✓ *U.S. holds high comp adv*

▨ *Key dimension*

Segment	Summary Rating	Raw Material Availability	Intellectual Property	Technical Leadership	Low Operational Costs	Demand / Supply Side Policies	Relative market maturity	Regulatory env. & infrastructure
EV – OEM	🟩		▨	▨ ✓		▨ ✓		✓
EV - Aftersales services	🟩		▨ ✓	▨ ✓			✓	
EV - Battery & powertrain manufacturing	▤		▨	▨ ✓		✓		▨
EV – Software	🟩		▨ ✓	▨ ✓			✓	
EV - Raw materials	🟨	▨ ✓				✓		▨
LDES – OEM	▤		▨			✓	✓	▨ ✓
LDES - O&M software	🟨			✓			✓	✓
Low-carbon Hydrogen – OEM	▤	▨	▨			▨ ✓	✓	
Low-carbon Hydrogen - Transport & Storage	🟩		▨			▨ ✓		▨ ✓
Low-carbon Hydrogen - Project Dev.	▤				▨ ✓	▨ ✓		
Advanced SMRs – EPC	🟨						▨	
Advanced SMRs – OEM	🟩		▨ ✓	▨ ✓		✓	✓	▨ ✓
Advanced SMRs – Raw Materials	▤	▨		✓		✓	▨	▨ ✓
DAC - EPC	▤			✓	▨ ✓			✓
DAC - Transportation & Storage	🟩	▨ ✓	✓	▨ ✓	▨ ✓	▨ ✓	✓	▨ ✓
DAC - OEM	▤	✓	▨ ✓	✓	▨	▨	✓	
DAC - Project Development	🟩	▨	✓	✓	▨ ✓	▨	✓	▨ ✓
DAC - Offtake	▤			✓	▨	▨		▨
Clean Steel - Offtake	▤					▨		▨ ✓
Clean Steel – OEM	🟨		▨			▨	▨	
Clean Steel - EPC	🟨					▨		

🟩 *U.S. has a strong existing competitive advantage and should maintain it*

▤ *U.S. has a potential to build a durable competitive advantage*

🟨 *U.S. should maintain status quo*

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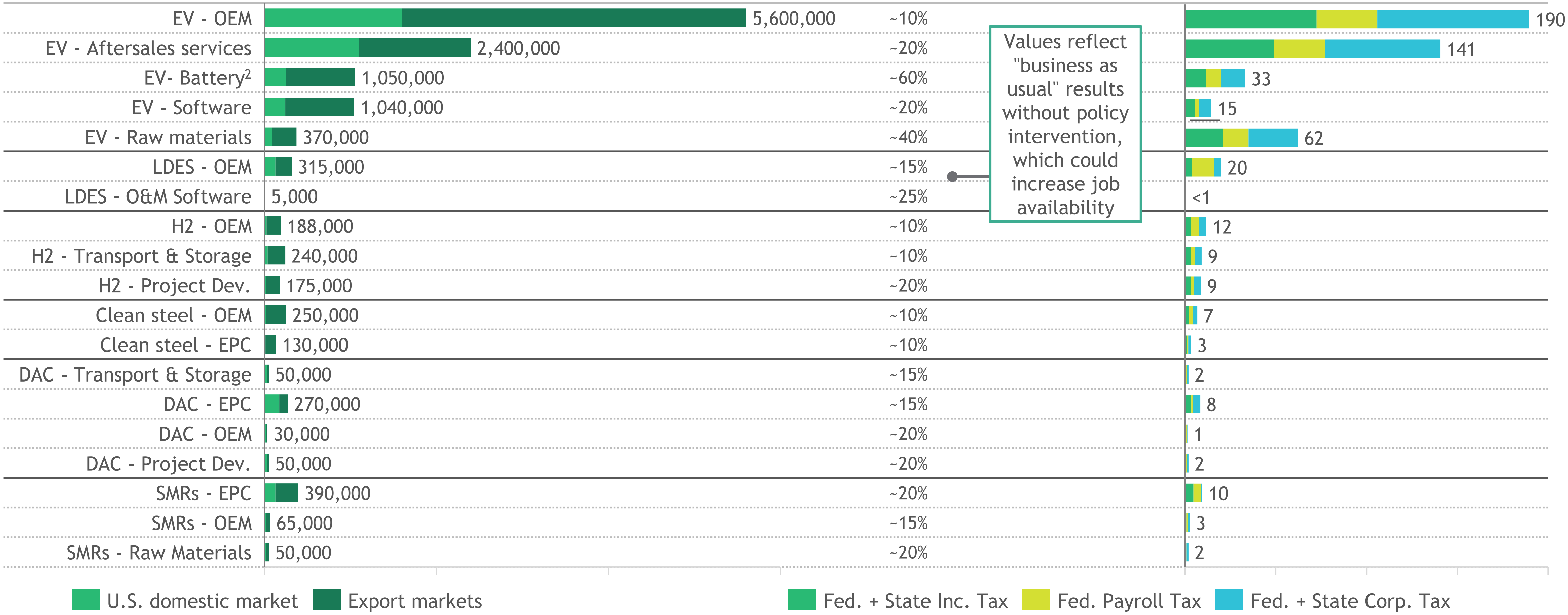
Societal impact | Policy intervention likely needed to spur job growth in disadvantaged communities



	Cumulative Domestic Job-years *2020 – 2050 (APS Scenario U.S. SOM)*	Proportion of jobs expected in target communities[1]	Cumulative Tax Impact ($B) *2020 – 2050, (APS Scenario U.S. SOM)*
EV - OEM	5,600,000	~10%	190
EV - Aftersales services	2,400,000	~20%	141
EV- Battery[2]	1,050,000	~60%	33
EV - Software	1,040,000	~20%	15
EV - Raw materials	370,000	~40%	62
LDES - OEM	315,000	~15%	20
LDES - O&M Software	5,000	~25%	<1
H2 - OEM	188,000	~10%	12
H2 - Transport & Storage	240,000	~10%	9
H2 - Project Dev.	175,000	~20%	9
Clean steel - OEM	250,000	~10%	7
Clean steel - EPC	130,000	~10%	3
DAC - Transport & Storage	50,000	~15%	2
DAC - EPC	270,000	~15%	8
DAC - OEM	30,000	~20%	1
DAC - Project Dev.	50,000	~20%	2
SMRs - EPC	390,000	~20%	10
SMRs - OEM	65,000	~15%	3
SMRs - Raw Materials	50,000	~20%	2

Values reflect "business as usual" results without policy intervention, which could increase job availability

1. Includes disadvantaged communities and communities impacted by the energy transition; 2. Battery & powertrain manufacturing
Source: White House Council on Environmental Quality (CEQ) Climate and Economic Justice Screening Tool; Resources for the Future "Mapping County-Level Exposure and Vulnerability to the US Energy Transition"; BCG analysis

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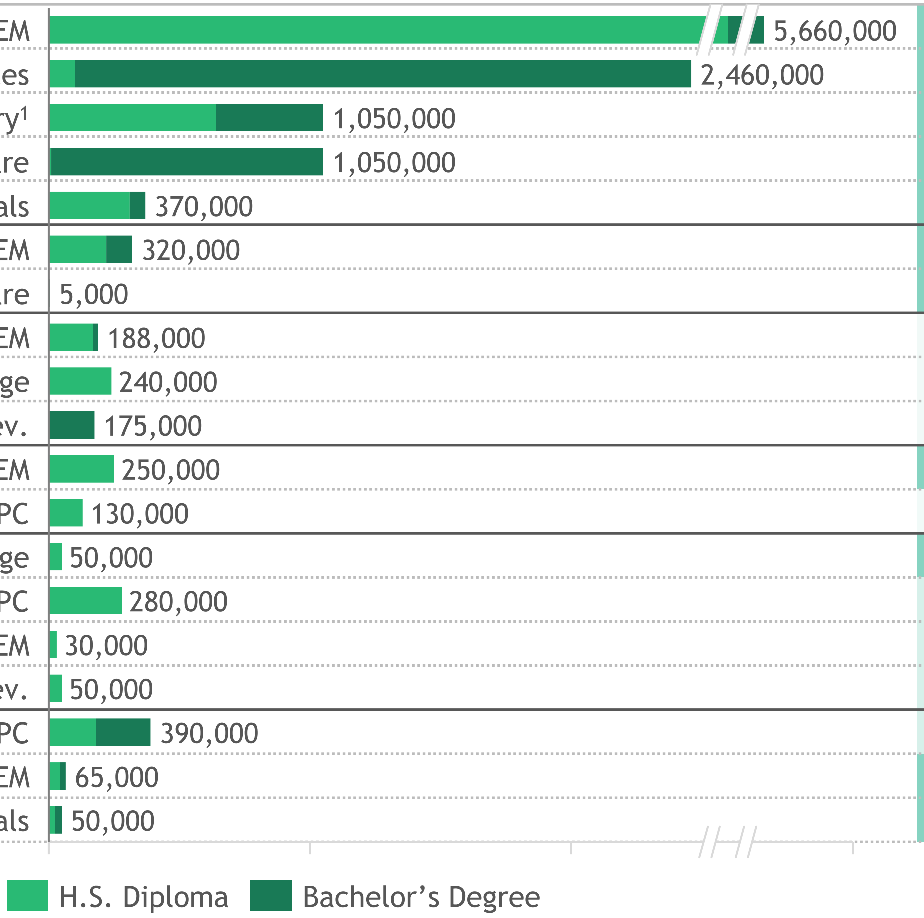
Job quality | EV OEM shows the largest opportunity to create jobs available to those without college degrees



	Cumulative Domestic Job-years 2020 – 2050 (APS Scenario U.S. SOM)	Avg. Job Duration (Years)	Est. Avg. Salary Avg. (Range)
EV - OEM	5,660,000	10+ yrs	$50 - 100K
EV - Aftersales services	2,460,000	10+ yrs	$100 - $150K
EV- Battery[1]	1,050,000	10+ yrs	$50 - 100K
EV - Software	1,050,000	10+ yrs	$100 - $150K
EV - Raw materials	370,000	10+ yrs	$50 - 100K
LDES - OEM	320,000	10+ yrs	$50K - 100K
LDES - O&M Software	5,000	10+ yrs	$100 - $150K
H2 - OEM	188,000	<3 yrs	$100 - $150K
H2 - Transport & Storage	240,000	<3 yrs	$50K - 100K
H2 - Project Dev.	175,000	<3 yrs	$50K - 100K
Clean steel - OEM	250,000	10+ yrs	$50K - 100K
Clean steel - EPC	130,000	<3 yrs	$50K - 100K
DAC - Transport & Storage	50,000	10+ yrs	$50K - 100K
DAC - EPC	280,000	5 - 10 yrs	$50K - 100K
DAC - OEM	30,000	10+ yrs	$100 - $150K
DAC - Project Dev.	50,000	5 - 10 yrs	$50K - 100K
SMRs - EPC	390,000	5- 10 yrs	$50K - 100K
SMRs - OEM	65,000	10+ yrs	$50K - 100K
SMRs - Raw Materials	50,000	10+ yrs	$100K - 150K

Majority of well-paying jobs are associated with higher levels of education

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1. Battery & powertrain manufacturing

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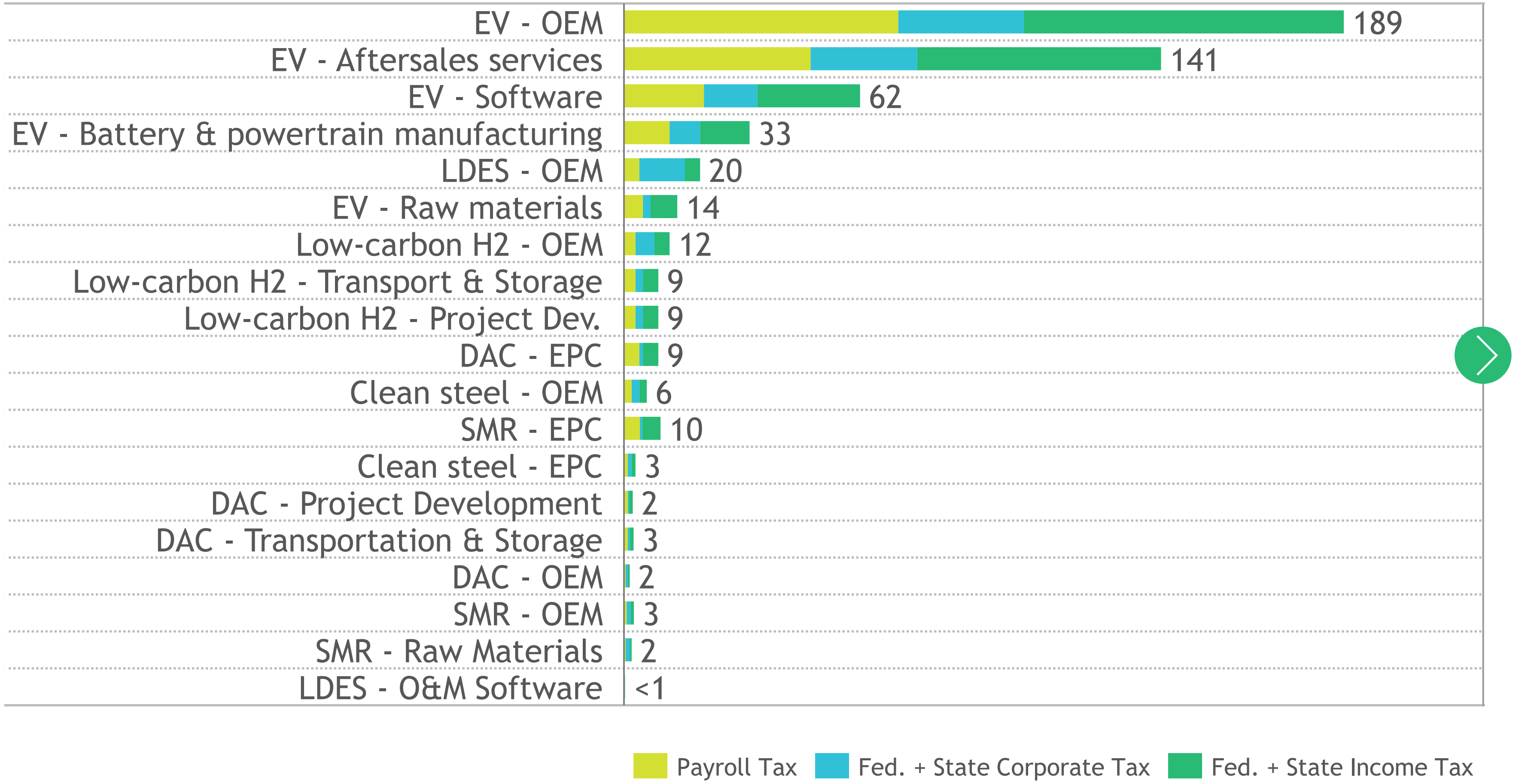
Tax Base | EVs have highest tax revenue potential due to largest market share

Cumulative Tax Impact

2020 – 2050, $B (APS Scenario)



Given income taxes make up largest portion of tax revenue growth (~45%) location of jobs will have a large impact on local tax income

1. Sum of FICA and MEDFICA tax rates used as a proxy for payroll tax (15.3%); 2. All values are '20-'50 cumulative tax revenues

Note: All numbers are rounded

Source: taxfoundation.org

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Summary enablers to unlock competitive advantage

Additional detail in following slides

Summary demand side enablers

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

Boost export competitiveness by **driving costs down the learning curve** by increasing total technology deployed

Summary supply side enablers

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

Boost export competitiveness by **building economies of scale** through investment in manufacturing **and maintaining lead in product quality** through R&D

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Several actions can enable competitive advantage across the six technologies evaluated

Policy-based **Investment-based**

Enabler type		Recommended action
Demand side	Decrease green premium	• Implement policies which **incentivize decarbonization or penalize emissions across the U.S. economy** (e.g., power, transport, industry) to increase demand for clean technologies and decrease demand for high-carbon substitutes
	Increase volume deployed	• Encourage technology-specific deployment mandates (similar to state RPS targets) to **incentivize technology deployment in the U.S.** • **Leverage U.S. government procurement power** through targeted procurement mandates to create initial product demand and de-risk investment in manufacturing
	Ensure access to export markets	• **Harmonize regulations and taxonomies between domestic and export markets** to ensure U.S. products can easily make inroads in priority export markets (e.g., harmonize nuclear licensing regulations, align clean hydrogen or carbon offset definitions)
Supply side	Streamline deployment	• **Streamline project permitting and application processes** to de-risk investment and shorten project timelines, improving access to private capital and lowering project costs
	De-risk project & infrastructure investment	• **De-risk private investment in domestic manufacturing, infrastructure, and projects** through low-cost financing and tax incentives to enable U.S. companies to quickly reduce costs via economies of scale
	Maintain lead in quality / cost through innovation	• Create opportunities to **increase research collaboration** among national labs, universities, and the private sector to build U.S. leadership in IP creation and R&D for long-term competitiveness • **Continue to fund research programs** to build U.S. leadership in IP creation and R&D for long-term competitiveness • Continue to **leverage cost-sharing agreements to demonstrate nascent technologies** with a focus on commercialization potential to overcome technology risks which deter private investment

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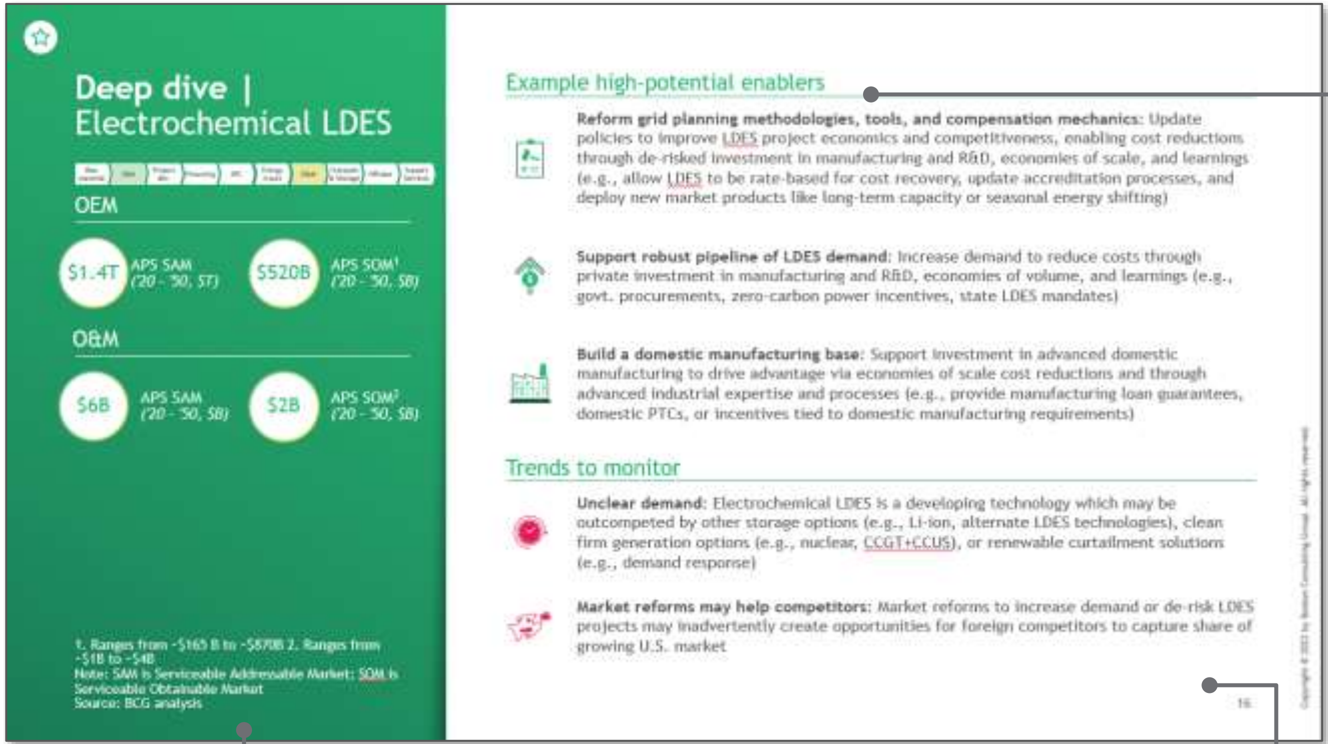
Context | Overview of Phase 3 findings



Deep dive | Electrochemical LDES

OEM

$1.4T APS SAM (20 - '50, $T)

$520B APS SOM^1 ('20 - '50, $B)

O&M

$6B APS SAM ('20 - '50, $B)

$2B APS SOM^2 ('20 - '50, $B)

1. Ranges from ~$165 B to ~$870B 2. Ranges from ~$1B to ~$4B
Note: SAM is Serviceable Addressable Market; SOM is Serviceable Obtainable Market
Source: BCG analysis

Example high-potential enablers

Reform grid planning methodologies, tools, and compensation mechanics: Update policies to improve LDES project economics and competitiveness, enabling cost reductions through de-risked investment in manufacturing and R&D, economies of scale, and learnings (e.g., allow LDES to be rate-based for cost recovery, update accreditation processes, and deploy new market products like long-term capacity or seasonal energy shifting)

Support robust pipeline of LDES demand: Increase demand to reduce costs through private investment in manufacturing and R&D, economies of volume, and learnings (e.g., govt. procurements, zero-carbon power incentives, state LDES mandates)

Build a domestic manufacturing base: Support investment in advanced domestic manufacturing to drive advantage via economies of scale cost reductions and through advanced industrial expertise and processes (e.g., provide manufacturing loan guarantees, domestic PTCs, or incentives tied to domestic manufacturing requirements)

Trends to monitor

Unclear demand: Electrochemical LDES is a developing technology which may be outcompeted by other storage options (e.g., Li-ion, alternate LDES technologies), clean firm generation options (e.g., nuclear, CCGT+CCUS), or renewable curtailment solutions (e.g., demand response)

Market reforms may help competitors: Market reforms to increase demand or de-risk LDES projects may inadvertently create opportunities for foreign competitors to capture share of growing U.S. market

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Example enablers summarize a subset of the most impactful levers to build U.S. competitive advantage in each clean technology

Trends to monitor stress areas where strategic moves or macroeconomic shifts will be critical to monitor & react to as the industry progresses

Market size, shown as both cumulative SAM and SOM in the APS scenario, show the relative opportunity size across segments

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Deep dive | Electrochemical LDES

Raw material › OEM › Project dev. › Financing › EPC › Energy Inputs › O&M › Transport & Storage › Offtake › Support Services

OEM

$1.4T APS SAM ('20 - '50, $T)

$173B APS SOM[1] ('20 - '50, $B)

O&M

$6B APS SAM ('20 - '50, $B)

$2B APS SOM[2] ('20 - '50, $B)

O&M only includes software segment[3]

Example high-potential enablers

Reform grid planning methodologies, tools, and compensation mechanics: Update policies to improve LDES project economics and competitiveness, enabling cost reductions through de-risked investment in manufacturing and R&D, economies of scale, and learnings (e.g., allow LDES to be rate-based for cost recovery, update accreditation processes, and deploy new market products like long-term capacity or seasonal energy shifting)

Support robust pipeline of LDES demand: Increase demand to reduce costs through private investment in manufacturing and R&D, economies of volume, and learnings (e.g., govt. procurements, zero-carbon power incentives, state LDES mandates)

Build a domestic manufacturing base: Support investment in advanced domestic manufacturing to drive advantage via economies of scale cost reductions and through advanced industrial expertise and processes (e.g., provide manufacturing loan guarantees, domestic PTCs, or incentives tied to domestic manufacturing requirements)

Trends to monitor

Unclear demand: Electrochemical LDES is a developing technology which may be outcompeted by other storage options (e.g., Li-ion, alternate LDES technologies), clean firm generation options (e.g., nuclear, CCGT+CCUS), or renewable curtailment solutions (e.g., demand response)

Market reforms may help competitors: Market reforms to increase demand or de-risk LDES projects may inadvertently create opportunities for foreign competitors to capture share of growing U.S. market

1. Up to ~$870B 2. Up to ~$4B 3.Software was prioritized given the potential for US competitive advantage
Note: SAM is Serviceable Addressable Market; SOM is Serviceable Obtainable Market
Source: BCG analysis

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Deep dive | Detailed list of potential electrochemical LDES policy actions to support U.S. competitiveness

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Technology-wide	☆ Incentivize zero-carbon firm energy and capacity ☆ Reform gid planning methodologies, tools, and compensation mechanics to fully consider range of benefits provided by LDES – Update IRP modeling tools to accurately evaluate LDES resources over time to drive demand – Allow LDES to be rate-based as a regulated transmission asset for cost recovery to de-risk project financing – Update accreditation processes for capacity markets (e.g., Effective Load Carrying Capability) to account for relative advantage of LDES as resource mix changes – Deploy new market compensation mechanisms to compensate LDES (long-term capacity contracts, seasonal energy shifting products, etc.) ☆ Encourage states to implement LDES mandates • Leverage fed. procurement power (e.g., defense facilities, federal power authorities like TVA) • Fund research into advanced grid modeling and integration studies to accurately quantify LDES benefits under a zero-carbon grid	• Fund demonstration project cost-sharing programs and research • Continue to facilitate research collaboration among National Labs, universities, and the private sector • Streamline domestic permitting, review, and approval timelines for LDES and renewable projects
OEM	• Include domestic content requirements for relevant LDES support mechanisms to incentivize domestic production of LDES components (e.g., ITC, public procurements)	☆ De-risk private investment in LDES manufacturing facilities via loan guarantees, cost-sharing, and / or tax credit programs
O&M Software	• *Included in Technology-wide section*	• *Included in Technology-wide section*

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Deep dive | Electric Vehicles

Battery & powertrain manufacturing

$4.4T APS SAM ('20 - '50, $T)

$470B APS SOM[1] ('20 - '50, $B)

OEM

$27T APS SAM ('20 - '50, $T)

$2.9T APS SOM[2] ('20 - '50, $T)

Software development

$4T APS SAM ('20 - '50, $T)

$430B APS SOM[3] ('20 - '50, $B)

Aftersales services

$9.2T APS SAM ('20 - '50, $T)

$1T APS SOM[4] ('20 - '50, $T)

1. Up to ~$2.6T 2. Up to ~$16T 3. Up to ~$2T 4. Up to ~$5.5T
Note: SAM is Serviceable Addressable Market; SOM is Serviceable Obtainable Market
Source: BCG analysis

Example high-potential enablers

Reduce supply-side investment risk: Launch initiatives that provide federal support to catalyze private-sector investment in critical companies focused on mineral extraction/processing and battery production (e.g., loan guarantees, manufacturing tax credits, local incentives)

Continue to support basic research & development: Invest in R&D across the battery, robotics, autonomy/ML, and semiconductor segments to retain & advance the U.S. innovation lead (e.g., grow funding for critical EV-related areas such as AI/ML, automation and robotics, semiconductors/chip design, and battery chemistry)

Invest in domestic & foreign mineral extraction & processing: Secure access to both domestic and foreign mineral reserves by coordinating public and private investments. Support domestic extraction and processing through streamlined permitting and supply-side support to accelerate growth

Trends to monitor

Growing scale: Investment in Asia, particularly in China, continues to outstrip the U.S. across the upstream value chain, including OEM production, driving a virtuous cycle of reinvestment, scale, automation, and cost reduction

Supply chain integration: As East Asia continues to invest in vertical integration, they may entrench cost advantages that will require prohibitive investment to replicate

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Deep dive | Detailed list of potential electric vehicle policy actions to support U.S. competitiveness (I/II)

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Technology-wide		☆ Continue funding broad-based research programs, including within DoD, NSF, DoE, ARPA-E, to invest in next-generation capabilities across battery chemistry, raw material extraction & innovation, automation & robotics, and AI/ML & computing ☆ Establish initiatives that reduce supply-side investment risk, such as extending the 48C manufacturing tax credit across segments, with focus on raw materials and battery production • Continue loans funding the buildout of a nationwide charger network to support consumer adoption
Raw materials	☆ Strong near-term production incentives for battery mineral processing & recycling, with clear & gradual phase-down periods, will accelerate domestic industry investment by reducing the premium for U.S. minerals • Export tariffs for EoL batteries w/ valuable chemistries (e.g., NMC) would reduce U.S. mineral leakage & support recycling ecosystem in long-term	☆ Leverage U.S. investment/financial entities including EXIM[1], DoD, DFC[2], Treasury to coordinate industry investments in foreign mineral extraction operations & secure equity share in production ☆ Standardize & streamline new extraction site permitting processes, working with environmental stakeholders from Phase 0 to drive alignment, including creating a defined review & comment period for new permit requests that limits timeline creep, and expanding FAST 41-style permitting coordination program for mineral extraction & processing • Continue growth of efforts such as DoE LPO to support growth in mineral processing capacity through loan guarantees & construction grants • Opening public lands to extraction with programs such as the DPA[3], alongside sufficient environmental standards, will help drive supply growth & reduce permitting hurdles ☆ Develop agreements with favorable tariff/trade structures for minerals from other countries to supply processing capacity within U.S. for critical minerals
Battery & powertrain manufacturing	• Create near-term production tax credit for battery manufacturing to drive industry scale	☆ Loan guarantee programs within DoE, in combination with DPA & federal grants programs, are important to scaling battery manufacturing capacity with a focus on U.S.-based entrants & new technologies • Create strong collocation centers for battery input material & manufacturing capacity to improve industry economics, leveraging favorable localized zoning, permitting, grants, and tax incentives to drive partnerships • Provide tax incentives for battery manufacturers using U.S.-made cell materials, with larger incentives for next-generation technologies to support initial scale for emerging players • Subsidize construction of manufacturing capacity with cutting-edge technology component to increase success rate of new startups

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1. Export-Import Bank of the U.S. 2. U.S. International Development Finance Corporation 3. Defense Production Act

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Deep dive | Detailed list of potential electric vehicle policy actions to support U.S. competitiveness (II/II)

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
OEM	☆ Extend existing broad-based, non-discriminatory EV consumer purchase tax credit to boost consumer demand by reducing the EV green premium • Shift large-scale domestic federal fleets (e.g., DoD, USPS, DoT) to EVs to provide additional demand baseline	☆ Provide public loan guarantees to small-scale EV companies to assist in initial scaling to achieve commercial viability • Create retraining & upskilling programs for automotive production & maintenance workers to build EV-capable workforce, including creating EV course materials for junior colleges and sponsoring training programs for high-skill EV-specific capabilities, such as systems engineering, battery engineering, EV powertrain production, and manufacturing automation • A dearth of experienced production, automation, and battery engineers may be a constraint in growth, and supporting a skilled workforce with a tailored immigration policy can help bolster the domestic skill pool • Help OEMs achieve manufacturing economics by establishing incentives & permitting policies that favor collocation along the supply chain, including across materials, battery, and powertrain production and OEM manufacturing production
Software & aftersales services		• Develop policy guidelines for states & municipalities to create non-prohibitive testing environments for early AV deployment • Implement proactive, standardized regulation that creates safe, practical, achievable targets for commercial AV applications ☆ Expand funding of research & development programs related to next-generation vehicle technologies, including AI, machine learning, sensors, and next-generation chip research ☆ Continue & grow broad-based efforts to on-shore semiconductor production to secure access to vital chip supply chains required to run advanced capabilities - Supporting scaling domestic chipmaking by providing facility grants/loans & demand-side domestic production incentives for both domestic & foreign manufacturers to grow manufacturing within U.S. - Cost sharing programs, analogous to the 48C tax credit, may help accelerate investments in domestic chip manufacturing sites

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Deep dive | Low-Carbon Hydrogen

Raw material	OEM	Project dev.	Financing	EPC	Energy Inputs	O&M	Transport & Storage	Offtake	Support Services

OEM

$510B APS SAM ('20 - '50, $B)

$100B APS SOM[1] ('20 - '50, $B)

Project Development

$120B APS SAM ('20 - '50, $B)

$24B APS SOM[2] ('20 - '50, $B)

Transport & Storage

$270B APS SAM ('20 - '50, $B)

$55B APS SOM[3] ('20 - '50, $B)

Offtake

$2.7 APS SAM ('20 - '50, $B)

$611B APS SOM[4] ('20 - '50, $B)

1. Up to ~$115B 2. Up to ~$30B 3. Up to ~$60B 4. Up to ~$809B

Note: SAM is Serviceable Addressable Market; SOM is Serviceable Obtainable Market

Source: BCG analysis

Example high-potential enablers

Work with foreign trading partners to ensure methane-derived H_2 (e.g., blue or turquoise) is acceptable under their net-zero targets: Country-specific policies related to low vs. zero carbon product use and import may restrict U.S. H_2 exports

Scale affordable renewable energy to enable cost-competitiveness of domestic low-carbon H_2 production by streamlining project development and providing renewable energy incentives

Invest in novel transport technologies and repurposed infrastructure for H_2 to achieve significant cost-reductions for transport and enable export/import of H_2 or end products

Use centralized project development (e.g., U.S. Regional H_2 hubs) to de-risk project development, facilitate cost sharing, and enable industrial-sized applications of emerging H_2 production technology

De-risk H_2 production by increasing H_2 demand through government procurement agreements or incentives for uptake/conversion

Trends to monitor

Net-zero targets and policies: More aggressive net-zero targets and policies can increase demand for decarbonization efforts in heavy-emitting industries, and lead to increased H_2 demand

Performance of low-cost Chinese electrolysers: Reliability improvements of low-cost Chinese electrolysers will decrease the ability of the U.S. to compete in OEM with its higher cost and efficacy electrolysers

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Deep dive | Detailed list of potential hydrogen policy actions to support U.S. competitiveness (I/II)

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Technology-wide	☆ Align on standards and acceptance (e.g., carbon intensity, H_2 taxonomy, certificate of origin, acceptability with emissions targets) for low-/zero- carbon $H_2$with key import regions (e.g., EU) ☆ Establish government procurement goals and agreements for H_2 end-use to create clear signals for low-carbon H_2 demand • Incentivize hydrogen (and H_2 derivatives) uptake (e.g., zero-carbon fuel standard, industry-specific abatement costs) • Provide financial incentives (e.g., tax credits, grants) to lower H_2 production costs	
OEM	☆ De-risk OEM innovation, integration, and industrial-scale pilots (e.g., cost-sharing agreements, support industrial-sized PEM & SOE electrolyser integrations)	• Support development expenses and de-risk industrial-scale projects • Continue financing novel electrolyser technologies (e.g., DOE research and H_2 shot funding) • Create opportunities and processes to increase research collaboration among national labs, universities and private sector ☆ Building of gigfactories for scaled electrolyser manufacturing
Project Development		• Streamline and prioritize review/approvals process for zoning, safety, and environmental impact ☆ De-risk nascent industrial-scale projects (e.g., low-cost development financing, cost-sharing agreements) • Scale affordable, renewable/low-carbon energy development (e.g., streamlined project development for co-located energy facilities, incentives for renewable energy development) • Continue investment in centralized infrastructure (e.g., DOE H_2 hubs funded in IIJA)

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Deep dive | Detailed list of potential hydrogen policy actions to support U.S. competitiveness (II/II)

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Transport & Storage	• Continued increase of hydrogen offtake, especially in hard-to-abate sectors (aviation, steel, etc.), which will increase need for transport/storage infrastructure	• Incentivize private sector to repurpose natural gas infrastructure • Create opportunities to increase collaboration between national labs, universities & private sector on novel transportation IP, like liquid organic hydrogen carriers ☆ Continue supporting novel H_2 transport technologies (e.g., LOHCs, ammonia cracking) and infrastructure projects (e.g., IIJA funding for Regional Hydrogen Hubs)
Offtake	Relevant actions are included in Technology-Wide section	

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Deep dive | Advanced Nuclear SMRs

Raw material | OEM | Project dev. | Financing | EPC | Energy Inputs | O&M | Transport & Storage | Offtake | Support Services

Raw materials

$30B APS SAM *('20 - '50, $B)*

$7B APS SOM[1] *('20 - '50, $B)*

OEM

$150B APS SAM *('20 - '50, $B)*

$37B APS SOM[2] *('20 - '50, $B)*

EPC

$170B APS SAM *('20 - '50, $B)*

$43B APS SOM[3] *('20 - '50, $B)*

1. Up to ~$11B 2. Up to ~$55B 3. Up to ~$65B
Note: SAM is Serviceable Addressable Market; SOM is Serviceable Obtainable Market
Source: BCG analysis

Example high-potential enablers

Enable needed economies of volume: De-risk private investment in manufacturing facilities to enable domestic players to achieve economies of volume (e.g., loan guarantees, cost sharing programs, tax credits)

Support robust pipeline of SMR demand: Increase demand to reduce costs through private investment in manufacturing and R&D, economies of volume, and learnings (e.g., govt. procurements, zero-carbon power incentives)

Build domestic HALEU production capacity: Incentivize private investment in U.S. HALEU production capacity to ensure commercial supply for U.S. projects and exports (e.g., govt. purchasing guarantees, loan guarantees, tax credits)

Increase export market access: Harmonize regulations and licensing requirements via NRC engagement with regulators in export markets to ensure U.S. products will meet regulatory requirements abroad

Trends to monitor

DOE HALEU availability program: The DOE is actively crafting a program to enable U.S. HALEU production, though results have yet to be announced

Progress of state-backed competitors: Large state-backed nuclear companies in Russia and China are researching advanced reactor technologies and may soon begin developing export opportunities

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Deep dive | Detailed list of potential advanced nuclear SMR policy actions to support U.S. competitiveness

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Technology-wide	☆ Incentivize zero-carbon firm power and capacity ☆ Harmonize regulations and licensing requirements with target markets via bilateral NRC engagement • Provide low-cost project financing to facilitate exports via U.S. Ex-Im Bank	• Continue demonstration project cost-sharing programs ☆ Launch commercialization-focused cost-sharing programs to prioritize technologies with both commercial and technical potential • Streamline domestic permitting, review, and approval timelines for SMR projects • Improve and facilitate stakeholder engagement and education to maintain project timelines
Raw materials	☆ Provide govt. purchasing guarantee for HALEU production to de-risk initial investment in enrichment	• De-risk private investment in enrichment facilities via loan guarantees, cost-sharing, and/or tax credits • Facilitate partnerships for uranium supply with trusted partners (e.g., Canada, Australia)
OEM	• Facilitate spent fuel waste management programs (e.g., re-import to U.S. or partner with third party) ☆ Procure SMR projects for relevant govt. facilities (e.g., national labs, military bases) to incentivize private investment in SMR manufacturing at scale	• Facilitate NRC licensing process for innovative advanced reactor designs • Continue to facilitate research collaboration among National Labs, universities, and the private sector ☆ De-risk private investment in SMR manufacturing facilities via loan guarantees, cost-sharing, and / or tax credit programs
EPC		• Streamline permitting process for domestic SMR projects to give domestic EPC firms SMR experience

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Deep dive | Direct Air Capture

Raw material | OEM | Project dev. | Financing | EPC | Energy Inputs | O&M | Transport & Storage | Offtake | Support Services

OEM

$131B APS SAM *('20 - '50, $B)*

$20B APS SOM[1] *('20 - '50, $B)*

Project Development

$60B APS SAM *('20 - '50, $B)*

$9B APS SOM[2] *('20 - '50, $B)*

EPC

$280B APS SAM *('20 - '50, $B)*

$42B APS SOM[3] *('20 - '50, $B)*

Transport & Storage

$141B APS SAM *('20 - '50, $B)*

$21B APS SOM[4] *('20 - '50, $B)*

Offtake

$1.6T APS SAM *('20 - '50, $B)*

$245B APS SOM[5] *('20 - '50, $B)*

1. Up to ~$40B 2. Up to ~$20B 3. Up to ~$85B 4.Up to ~$45B 5. Up to ~$490B
Note: SAM is Serviceable Addressable Market; SOM is Serviceable Obtainable Market
Source: BCG analysis

Example high-potential enablers

Continue to fund centralized domestic project development (e.g., U.S. DAC hubs) that can support diverse DAC technologies to de-risk project development, facilitate cost sharing, and enable industrial-sized applications of next generation OEM technology

Streamline CO_2 storage permitting: prioritize review process permits, environmental impact, and zoning to enable scaled DAC deployment

Scale affordable clean energy: Expedite deployment of renewable or low (bias towards zero)-carbon energy in co-located facilities to meet high DAC energy requirements

Align on offset quality/verification standards with main export partners that use lifecycle analyses and can adequately reflect high quality DAC credits

De-risk DAC deployment/investment in R&D by providing government procurement agreements for DAC credits and publicly funding site selection surveys to identify ideal locations for DAC facilities (incl. societal impacts)

Trends to monitor

Net-zero targets and policies: More aggressive net-zero targets and policies will increase demand for DAC to address hard-to-abate emissions

Trade regulations for main export partners: Regulations could restrict the trading of DAC carbon credits across borders (e.g., as in E.U. ETS), limiting DAC offtake market size and export potential

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Deep dive | Detailed list of potential DAC policy actions to support U.S. competitiveness (I/II)

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Technology-wide & Offtake	• Increase offtake demand via incentives & regulations (e.g., scope 3 emissions reporting, tax credits for storage or fuel switching) ☆ Establish quality and verification standards for DAC credits (e.g., permanence, resource intensity, etc.) and align on standards with key export partners to ensure offtake and de-risk market for buyers • ☆ Leverage public procurement for DAC offsets and synfuels/ low carbon DAC products to accelerate cost reductions & scaling • Develop or expand carbon credit markets that allow cross border sales (e.g., existing public sector example - California LCFS)	• Increase DAC offtake creation (offsets & DAC CO2 utilization) via incentives (e.g., tax credits) to reduce costs • Invest in low-carbon CO2 utilization technology & provide incentives or low-cost financing for project deployment (e.g., synfuel facility) • Continue investment in renewable and low-carbon energy
OEM[1]		☆ Continue investments in IP R&D for next-generation DAC technology with higher efficacy & energy efficiency (e.g., DoE Funding Program) ☆ Continue centralized project development (e.g., DAC hubs) that de-risk projects for OEMs, enable cost sharing, and enable industrial-sized applications of OEM technology • Create opportunities and processes to increase research collaboration among national labs, universities and private sector
Offtake	Relevant actions are included in Technology-Wide section	

[1] OEMs may also function as Project Developers (e.g., Climeworks), so interventions may be cross-applicable for these segments

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Deep dive | Detailed list of potential DAC policy actions to support U.S. competitiveness (II/II)

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Project Development[1]	• Create centralized, standardized RFPs for DAC facilities or OEM inclusion in hub infrastructure to enable competition • De-risk offset purchases through government assumption of liability for long-term CO2 storage beyond a required time window	☆ Streamline and prioritize review/approvals process for CO2 storage permits, environmental impact, and zoning • Continue providing necessary infrastructure (e.g., DAC hubs with energy, compression, etc.) to enable smaller OEMs with diverse technology and needs to deploy their technology at scale to accelerate learnings and cost reductions ☆ Publicly-fund site selection surveys to identify ideal locations for DAC facilities, including environmental conditions & societal impact • Provide low-cost financing to de-risk nascent commercial projects ☆ Invest in domestic renewable/low-carbon energy facility development in ideal DAC locations to enable DAC scaling • Provide incentives for companies to invest in using waste heat or infrastructure from existing infrastructure to support co-located DAC
EPC	• Incentivize use of domestic EPC players for DAC facility creation to gain experience and increase competitiveness for exported EPC	
Transport & Storage		☆ Continue to allocate funding for DAC hubs and related transport and storage infrastructure • Streamline storage permitting and potential revisit existing storage well permitting to retain rigorous environmental standards, while reflecting the low risks for geologic storage; streamlining legal processes accelerates scaling & lowers costs

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1. OEMs may also function as Project Developers (e.g., Climeworks), so interventions may be cross-applicable for these segments

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Deep dive | Clean Steel

Raw materials | OEM | Financing | EPC | Energy Inputs | O&M | Offtake | Support Services

OEM

$920B APS SAM *('20 - '50, $B)*

$50B APS SOM[1] *('20 - '50, $B)*

EPC

$270B APS SAM *('20 - '50, $B)*

$15B APS SOM[2] *('20 - '50, $B)*

Offtake

$5.4T APS SAM *('20 - '50, $T)*

$280B APS SOM[3] *('20 - '50, $B)*

1. Up to ~$140B 2. Up to ~$40B 3. Up to ~810B
Note: SAM is Serviceable Addressable Market; SOM is Serviceable Obtainable Market
Source: BCG analysis

Example high-potential enablers

Expand demand-side support: Incentivize domestic clean steel offtake (e.g., subsidies for carbon capture & sequestration, carbon border adjustment), building on the lower carbon intensity of U.S. steel production today

Stimulate demand with federal procurement: Use federal contracts to jump-start the clean steel industry, while streamlining the contracting process to enable new entrants to compete

Align on standardized, public carbon accounting with domestic steel producers and export partners to certify steel production emissions intensity

Invest in R&D and scaling of CCUS: Fund CCUS R&D and de-risk commercial-scale deployment to maintain the small lead by the U.S. today and prevent other nations from leapfrogging U.S. and taking market share

Trends to monitor

Increased policy momentum: Regions such as Canada and the E.U. are leading in steel decarbonization policy, which may rapidly accelerate the growth of clean steelmaking players in those nations and enable domestic players to replace U.S. imports

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Deep dive | Detailed list of potential clean steel policy actions to support U.S. competitiveness

Policy-based Investment-based ☆ Key interventions

	Demand side	Supply side
Technology-wide	☆ Incentivize U.S. clean steel offtake by imposing demand-side border adjustment/tariffs (U.S. steel industry has low relative carbon intensity). A carbon tariff of ~$80-110/ton would bring existing clean steelmaking methods including DRI-EAF w/ CCUS to commercial viability and accelerate commercial scaling of next-generation methods such as 100% hydrogen-based DRI ☆ Leverage department-level federal procurement (e.g., DoD) to provide demand baseline through regulations such as a minimum % clean steel requirement in contracts	• Work in parallel with grid-focused incentives to decarbonize electricity supply
OEM	☆ Incentivize investment in installation of CCUS systems (e.g., subsidies, expansion of existing 45Q tax credit)	• Loan guarantee programs can assist smaller steelmakers with transitioning to carbon-capture and DRI-EAF based steelmaking • Support innovation of emerging steelmaking technologies in the domestic market, such as molten oxide electrolysis and 100% hydrogen-based DRI (e.g., grants & loan guarantee programs) • De-risk steelmaking facility investment in CCUS integration (e.g., cost sharing programs, renewed 48C manufacturing subsidy)
EPC		• Increase domestic CCUS development by supporting construction & buildout of carbon transportation infrastructure (e.g., SCALE Act) • Continue funding CCUS infrastructure buildout efforts (e.g., DoE CarbonSAFE) • Continue buildout of centralized project hubs (e.g., U.S.-based hydrogen hubs) and sponsor steelmaker collocation to support pilot hydrogen-based DRI facilities
Offtake	☆ Implement standardized carbon-tracking mechanism to monitor & certify carbon intensity of steel production, both domestic & imported (as relevant and practical in CBAM scenario) ☆ Incentivize uptake of clean steel (e.g., government cost-sharing for companies sourcing clean steel)	• Support the standardized documentation (e.g., emissions intensity) & acceptance of clean steelmaking within federal codes for broader set of applications

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Technology-specific findings

LDES

Electrochemical LDES | Definition of each segment across value chain

Raw materials & inputs	OEM	Project Development	Financing	EPC	Operations/ Maintenance	Transport & Storage	Offtake
Mining and refining of raw materials for: **Electrolytes** (Vanadium, Bromine, Zinc, Iron) **Battery cells** (plastics, metal containers, flow membrane, etc.) **Balance of plant** (metals, wiring, etc.)	**R&D:** Significant R&D is ongoing to further refine LDES technologies **Component manufacturing:** Assembly of component pieces (e.g., piping, pumps, refined electrolytes, etc.) **Battery cell manufacturing:** Assembly of battery cells without balance of plant yet included **Final manufacturing:** At scale, includes manufacturing of final standardized DC battery packs / systems	**Development includes:** • Origination • Site selection • Permitting • PPA structuring • Inter-connection queue • Insurance / project guarantee May be developed in tandem with a renewable project or standalone Customers may be utilities, renewable developers, corporate clients, or industrial users	Developer typically arranges project financing Financing is often difficult as storage revenue streams are difficult to model and are evolving	EPC includes: • Final site engineering • On-site DC battery pack installation • Final AC inter-connection and testing EPC process may be done in tandem with a paired renewable project or can be standalone	**Operations:** Charging / discharging is typically run by software which informs how LDES should bid into the market. Optimized software is key to fully capturing the value stack of a LDES project **Maintenance:** Includes testing electrolyte tanks for leaks or imbalances, maintaining pumps, and measuring capacity degradation. Predictive maintenance & monitoring tools can reduce O&M costs	Completed battery packs can be transported using conventional rail / truck / shipping Transport of electrons is provided by new / existing transmission lines (likely to site in areas with transmission access)	Stored power is injected into the bulk electric system, local microgrid, or as behind-the-meter storage LDES can provide multiple sources of value in electricity markets, however current market mechanisms do not fully recognize and compensate LDES for all value streams

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

Additional analysis in Phase 2

High	Medium	Low	N/A

Note: Market size numbers are agnostic of LDES technology

	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

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Electrochemical LDES | Raw materials & inputs

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

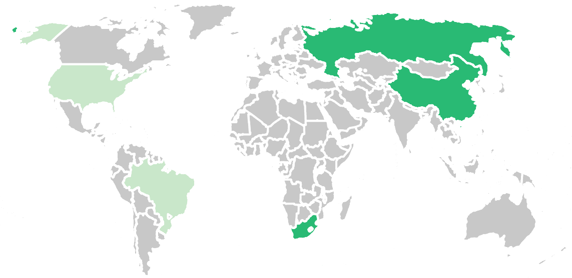
Raw materials & inputs for LDES include the battery electrolytes (vanadium, zinc, and bromine), electrodes (e.g., iron), and additional components which make up the balance of plant (e.g., plastics, metals, wiring, etc.). Most inputs, with the exception of vanadium, are widely available and relatively low-cost

$550 - 675B
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$5 - 10	$50 - 60	$10 - 20
Margin (%)	-	5 - 15%	5 - 15%	5 - 15%

GLOBAL PLAYERS - COUNTRIES



🟩 Vanadium production capacity >10 kT
▨ Vanadium production capacity <10 kT

COMPANIES

GLENCORE

LARGO RESOURCES

TECHNOLOGY

Nm Neometals

VALUE PROPOSITION

Despite the concentration of several critical inputs (such as iron, zinc, and vanadium), raw materials are unlikely provide significant value, as most of the critical LDES inputs are easily acquired via global commodity markets. This ease of access inhibits developing a durable competitive advantage

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	The production of a majority of critical LDES inputs (e.g., vanadium, zinc, bromine, etc.) are highly concentrated in a small number of countries. However, all inputs are easily obtained in global commodity markets, reducing the potential competitive advantage upside Vanadium has undergone a supply crunch in recent years, driving up the price in global commodity markets, however vanadium is still easily obtained via global markets	L

Source: BCG Analysis

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Electrochemical LDES | OEM

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

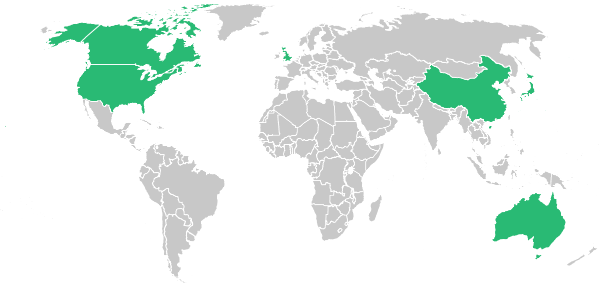
LDES OEM consists of both the manufacturing of battery cells as well as the final production of complete power blocks for on-site installation. While still a nascent area with many smaller players, significant cost reductions are expected in the OEM space as production capacity increases and economies of scale are achieved

$1,200-1,500B
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$20 - 30B	$100 - 110B	$25 - 35B
Margin (%)	-	10 - 15%	10 - 15%	10 - 15%

GLOBAL PLAYERS - COUNTRIES



🟩 Electrochemical OEM startups are present

COMPANIES

VRB ENERGY

INVINITY ENERGY SYSTEMS

SUMITOMO ELECTRIC

redflow

Form energy

ESS INC

eos

UET UniEnergy Technologies

融科储能 RONGKE POWER

VALUE PROPOSITION

OEM presents a clear opportunity to build durable competitive advantage in a high-value area, particularly around IP for new and emerging technologies. As IP is developed and refined, supportive policies to scale production and capture economies of scale can provide an early advantage for domestic players as well

EVALUATION

Market	**Competitive Advantage**	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Multiple countries are current directly subsidizing R&D for LDES technologies (e.g., $1.16B Energy Storage Grand Challenge fund in U.S., £68M Longer Duration Energy Storage Demonstration competition in the U.K.) and / or providing indirect incentives (e.g., tax credits)	H
IP & relevant technical expertise availability	Electrochemical LDES technology is still being developed and refined, with large potential competitive advantage for players which optimize the underlying technology and manufacturing process. ~20 companies are currently developing >10 specific technologies, creating potential for significant IP advantage	H
Financing access	Early LDES OEM players are successfully securing initial financing from niche market players such as VCs (e.g., Softbank) and early-stage startup investors. Some govt. subsidies are also available to fund R&D and technology demonstration projects	M

Source: BCG Analysis

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Electrochemical LDES | Project Development

High | Medium | Low | N/A

DESCRIPTION OF TECHNOLOGY

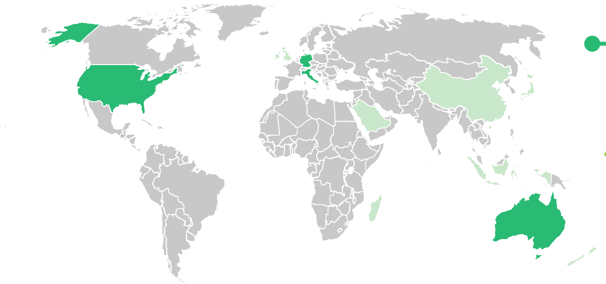
While LDES project development is driven by OEM players today, as the industry matures this may shift to be more similar to Li-ion development where standalone development companies drive projects and select from a range of technology providers based on project needs. LDES projects may be developed paired with renewables or as a standalone asset

$15 - 20B
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	<$1B	$1 – 2B	<$1B
Margin (%)	-	10 - 15%	10 - 15%	10 - 15%

GLOBAL PLAYERS - COUNTRIES



🟩 >5 projects operational or in development
🟩 1 - 5 projects operational or in development

COMPANIES

LDES OEM's developing projects

ESS INC
eos
SUMITOMO ELECTRIC
Form energy

Major renewable developers

NEXTera ENERGY
eDF
Invenergy

VALUE PROPOSITION

As LDES matures project development is expected to shift to a model similar to Li-ion, where standalone developers integrate OEM-provided technologies into their projects. The robust existing set of players (e.g., Invenergy, NextEra, etc.) may expand existing competitive advantage into the LDES space

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Trained/skilled labor force availability	Detailed understanding of regional power markets and permitting processes are required to successfully develop utility-scale LDES projects	M
Market ecosystem maturity	Development is largely done at the national or regional level, however some renewable development players (e.g., EDF, Invenergy, etc.) have begun to expand globally	M
Providers / supplier concentration	While there are several established leading renewable and storage developers (e.g., NextEra, Invenergy, etc.) the market as a whole is relatively fragmented, with the top five players owning <30% of the U.S. market[1]	L
Relevant infrastructure potential	Markets with insufficient transmission networks, such as the U.S., are expected to spur the growth of LDES deployment, creating potential for a more robust domestic market than other countries	L

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1. Based on announced development pipelines 2020 – 2024 according to S&P Global
Source: BCG Analysis

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Electrochemical LDES | Financing

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Financing LDES projects can be challenging, both due to technology risk and difficulties accurately projecting project cash flows for the complicated storage value stack. However, emerging offtake models such as a "build and flip" to utility rate base or contracted tolling agreements can provide dependable cash flows which support project financing

$40 - 50B
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	<$1B	$3 - 4B	$1 - 2B
Margin (%)	-	5 - 10%	5 - 10%	5 - 10%

GLOBAL PLAYERS - COUNTRIES

Not applicable
Financing is largely dependent on ultimate customer and is not limited to specific geographies

COMPANIES

Breakthrough Energy Ventures
Goldman Sachs
ArcelorMittal
Alfa Laval

VALUE PROPOSITION

Aside from macroeconomic factors which give specific countries competitive advantage in cost-effective financing, there are limited avenues to generate competitive advantage for LDES project financing. The existing U.S. ITC provides limited advantage near term, however as the ITC steps down this will diminish

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing environmental regulatory support	Specific situations, such as LDES paired with solar/wind, may quality for the U.S. ITC and enable tax equity project financing	M
Financing access	While access to financing has been an obstacle to storage project development, offtake models which create dependable project cash flows can reduce this difficulty. This is largely true for utility customers, who may purchase and rate base LDES assets outright using balance sheet financing, or who may opt for a fixed $ / kW / month tolling agreement recovered from ratepayers. Both structures provide certainty to financiers of project cash flows Technology and project risks may still complicate project financing and may limit the ability of utility customers to get regulatory approval for large projects. As the technology matures, however, this difficulty should subside	L

Source: BCG Analysis

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Electrochemical LDES | EPC

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

LDES EPC involves final on-site construction and AC interconnection of factory-produced DC battery packs. Sites may be standalone storage or paired with renewable projects, with either a common or separate EPC player. EPCs will often act as "integrators", combining the DC battery pack with other components for a functioning AC battery storage system

$1,200 - 1,400
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$10 – 20B	$110 – 130B	$30 - 40B
Margin (%)[1]	-	5 - 8%	5 - 8%	5 - 8%

GLOBAL PLAYERS - COUNTRIES

Not applicable
OEMs typically partner with local/regional players as needed

COMPANIES

BLACK & VEATCH

SIEMENS

BURNS & McDONNELL

GE

BLATTNER ENERGY

VALUE PROPOSITION

LDES EPC is unlikely to provide opportunity for durable competitive advantage, as the engineering skills/capabilities needed are similar to what many existing players possess today. Further, the construction element of EPC is typically highly local in nature, limiting any additional advantage there

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Trained/skilled labor force availability	Final LDES project installation may require some certified / specific types of labor (e.g., electricians) though large portions of construction will not (e.g., site preparation, structure assembly, etc.)	M
Pricing advantage potential	Given high degree of labor, local variations in labor costs can provide some degree of competitive advantage for LDES installation and site preparation. Experienced EPCs may reduce costs by avoiding delays / budget overruns	M

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1. Margins can range much higher for certain niche activities, however overall are expected to be low

Source: BCG Analysis

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Electrochemical LDES | Operations & Maintenance

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

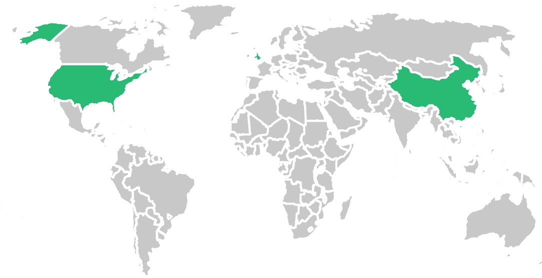
Similar to other Li-ion storage, LDES will likely be operated by sophisticated energy system mgmt (EMS) software to time charge/discharge cycles to fully capture the value LDES can provide. Maintenance is largely limited to monitoring and repairing both the mechanical and chemical battery components (e.g., electrolyte balances, pumps, electrodes, etc.)

$60 - 70
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	<1B	$3 - 4B	$4 - 5B
Margin (%)[1]	-	5 - 15%	5 - 15%	5 - 15%

GLOBAL PLAYERS - COUNTRIES



🟩 EMS software companies based in this country

COMPANIES

EMS software companies

res
CATL 宁德时代
stem
Geli

LDES owner / operators

Southern Company
Hecate Energy

VALUE PROPOSITION

Operations software presents an opportunity to build IP which can easily be defended and sold/licensed in other markets. The maintenance aspects of O&M are less lucrative and will generally be local in nature, leaving little room for competitive advantage

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Intellectual Property, technical expertise, and R&D availability	The operations software for battery storage technologies can be quite complex and is key to fully maximizing the asset value. As software, this can be a highly defensible area of IP which is still in the early stages of development. Several standalone battery software players (e.g., Geli) are already participating in the Li-ion space, with potential to expand to LDES as the technology matures as well	H
Trained/skilled labor force availability	O&M for LDES assets will likely require a moderately specialized labor force	M
Providers / supplier concentration	While still a highly nascent space, early energy system management software providers such as Geli and Stem appear well-poised to expand services in the increasingly specialized Li-ion storage market	N/A

Source: BCG Analysis

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Electrochemical LDES | Transport & Storage

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

LDES battery packs can be transported using conventional rail/truck/shipping, as completed packs are often housed in shipping containers. The power discharged by LDES will typically be injected into the grid and transported using bulk electric system high-voltage transmission lines

N/A
Cumulative US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
Market Size ($B)	*Not applicable*			
Margin (%)				

GLOBAL PLAYERS - COUNTRIES | COMPANIES

Not applicable
Transmission will be provided by the local utility and/or regional system operator (e.g., ISO/RTO)

VALUE PROPOSITION

Given the large amount of overlap with other industries, there is little direct opportunity related to transport and storage for LDES

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Relevant infrastructure potential	Markets with insufficient transmission networks, such as the U.S., are expected to spur the growth of LDES deployment, creating potential for a more robust domestic market than other countries	L

Source: BCG Analysis

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Electrochemical LDES | Offtake

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Power is charged/discharged into the bulk grid or microgrid. LDES can serve many use cases, including reducing renewable curtailments, deferring transmission buildouts, providing resource adequacy in capacity markets, or providing ancillary services such as inertia, frequency response, and other operating reserves

N/A
Cumulative US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
Market Size ($M)	*Not applicable*			
Margin (%)				

GLOBAL PLAYERS - COUNTRIES COMPANIES

Not applicable

Highly local nature of electricity offtake means that all EC-LDES will require access to transmission infrastructure or a local microgrid

VALUE PROPOSITION

Governments and regulators can help nurture a domestic LDES market by crafting policies & market mechanisms which ensure that LDES qualifies for and fully captures the value from the full range of services it can provide (e.g., capacity markets, ancillary services, etc.)

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing environmental regulatory support	LDES may struggle in certain markets to compete with legacy fossil fuel assets which provide similar services, such as firm capacity and ancillary services. Supportive policies which assign the cost of externalities to fossil fuel assets, such as a carbon tax, RPS, or cap and trade system, would ensure that LDES is able to compete in such markets. This would nurture a robust domestic market which may in turn enable exports to less-mature markets abroad	M
Market ecosystem maturity	While electricity markets have been in place for decades, the underlying market rules and mechanisms are not always able to fully compensate LDES for services provided. For example, in markets like ERCOT no capacity market exists which could compensate LDES for the resource adequacy benefits it provides, while in PJM LDES may not qualify for capacity markets due to the qualifying criteria in place	L

Source: BCG Analysis

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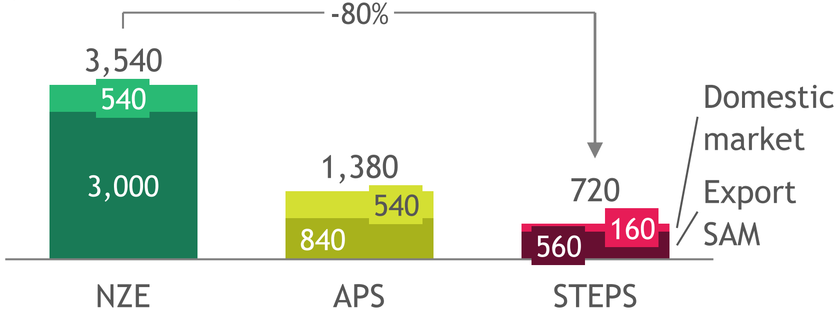
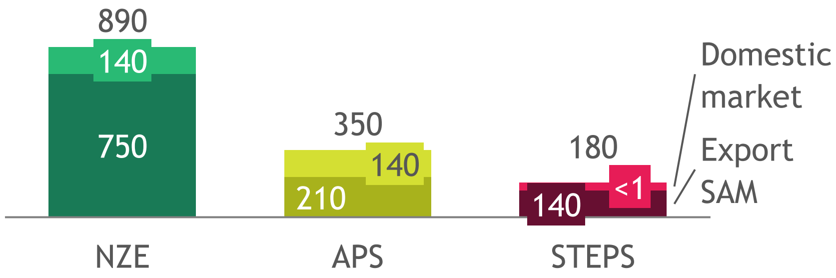
OEM offers strongest U.S. market opportunity across scenarios, though export potential falls ~40 - 60% from the Net Zero Emissions scenario

OEM

U.S. Serviceable Addressable Market (SAM)
(2020 - 2050, $B)



U.S. SAM Margin Pools
(2020 - 2050, $B)

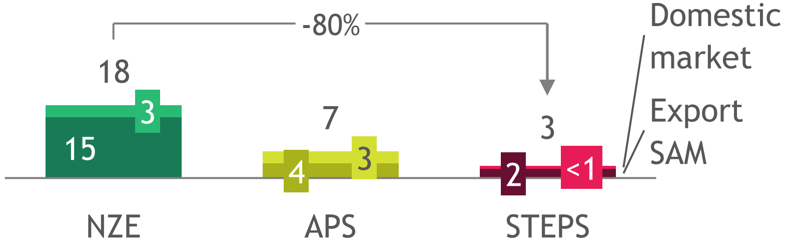


~20 - 30% Est. gross average margin

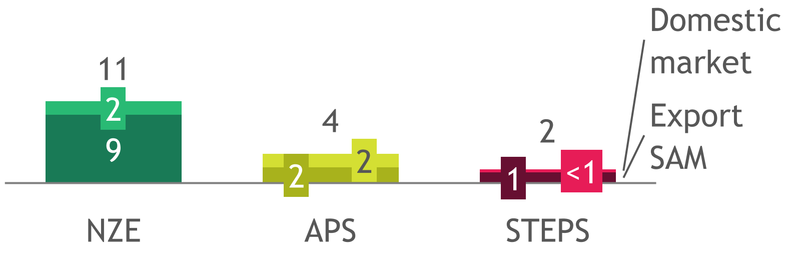
Note: *Scale for O&M has shifted for readability*

O&M - Operations Software

U.S. Serviceable Addressable Market (SAM)
(2020 - 2050, $B)



U.S. SAM Margin Pools
(2020 - 2050, $B)



~50 - 70% Est. gross average margin

Source: BCG analysis

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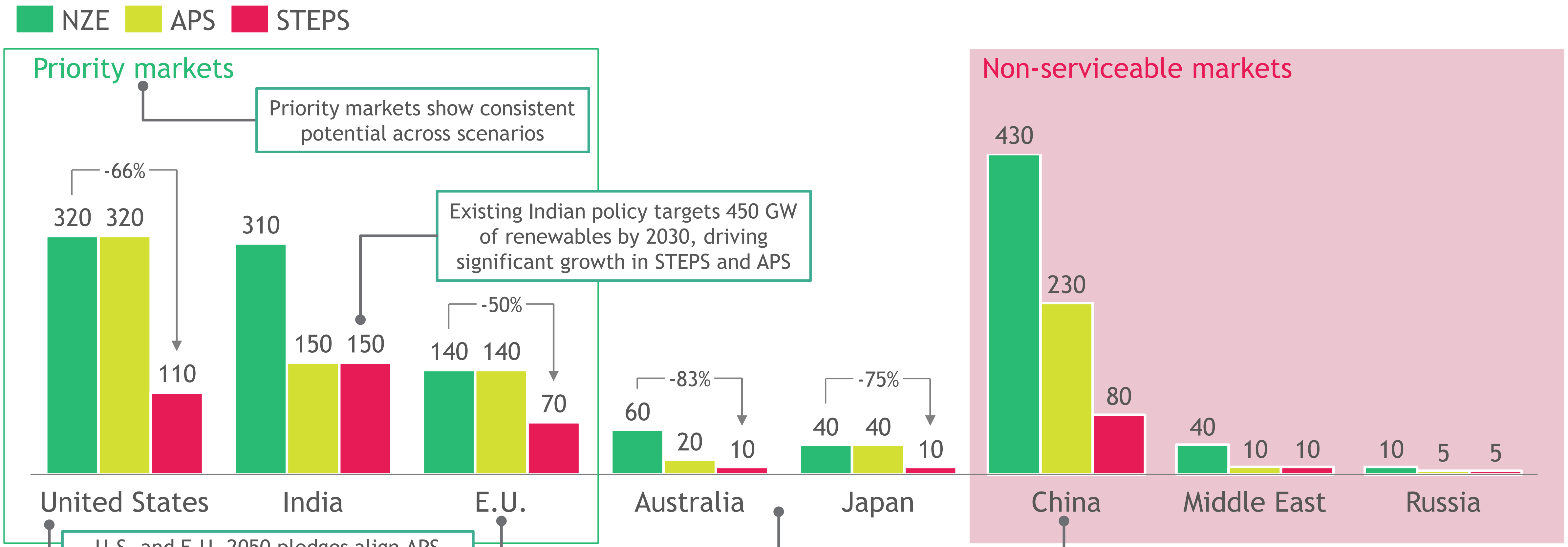
India and E.U. markets are dependable opportunities across scenarios, while the U.S. domestic market also presents large potential

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; BCG analysis

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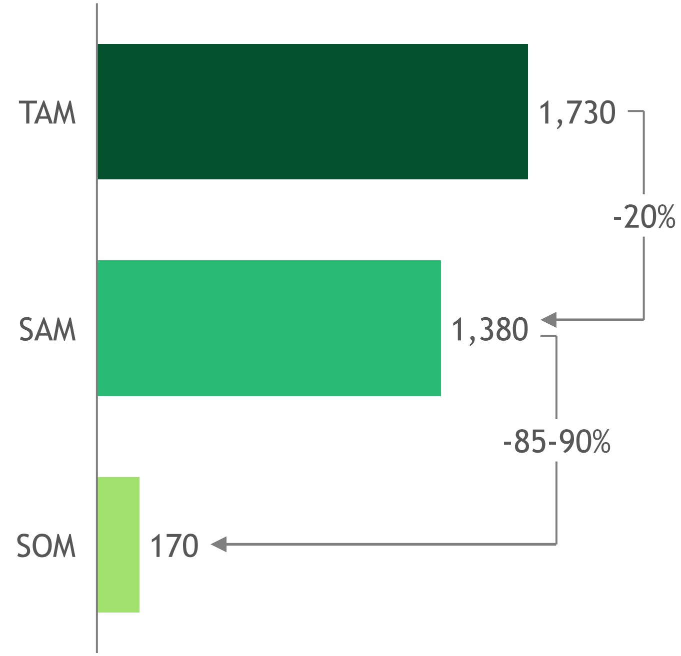
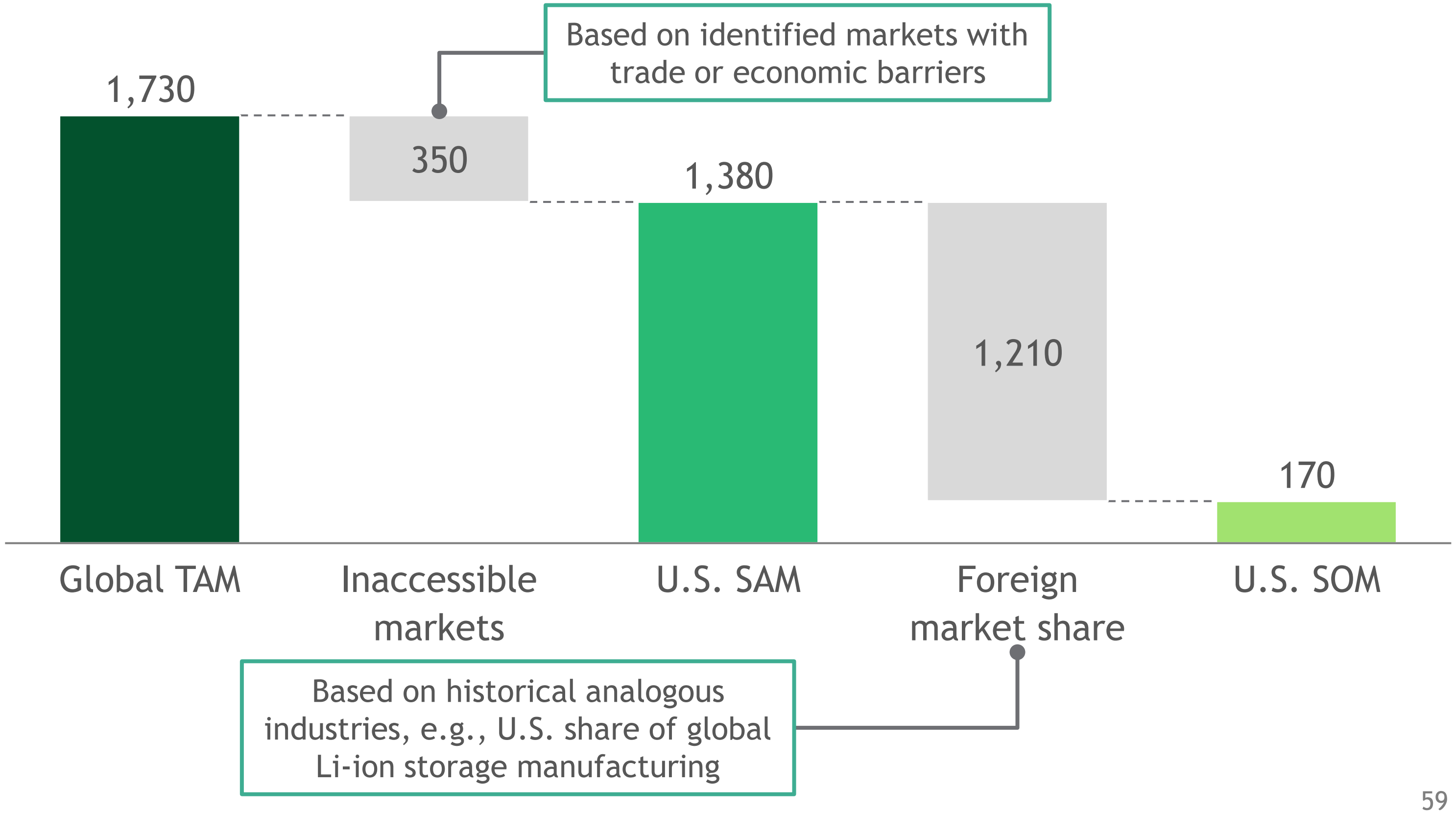
OEM | U.S. share of Li-ion storage manufacturing of ~10 – 15% implies a conservative potential U.S. SOM of ~$150 - 190B through 2050 for LDES OEM

APS market sizing metrics

Cumulative market value, 2020 – 2050 *($B)*



Walk from TAM to SOM under APS scenario



Based on identified markets with trade or economic barriers

Based on historical analogous industries, e.g., U.S. share of global Li-ion storage manufacturing

Source: IEA World Energy Outlook 2021; LDES Council, BCG analysis

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OEM | LDES OEM market is expected to spike ~2030 – 2040 across scenarios

Spike in NZE is driven by India and RoW, while the U.S. drives the spike in APS

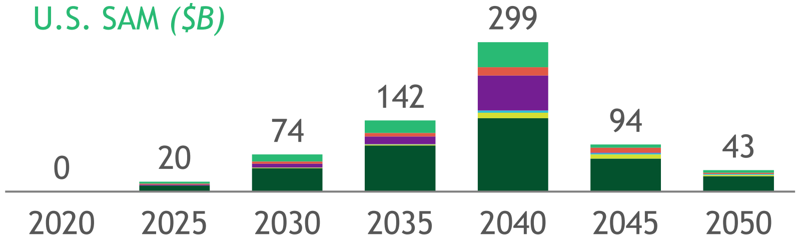
Net Zero Emissions Scenario

🟩 U.S. 🟥 E.U. 🟪 India 🟦 Japan 🟨 Australia ⬛ Rest of World

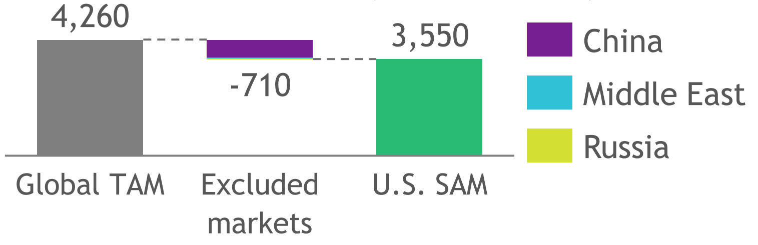
$3.5T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

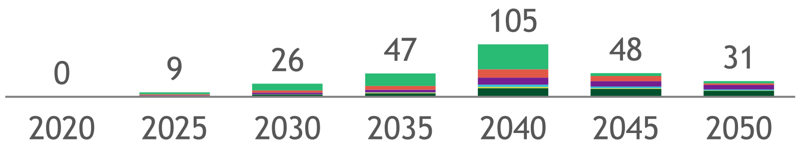


Announced Pledges Scenario

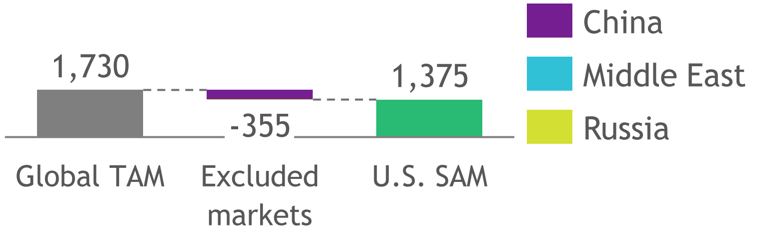
$1.4T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

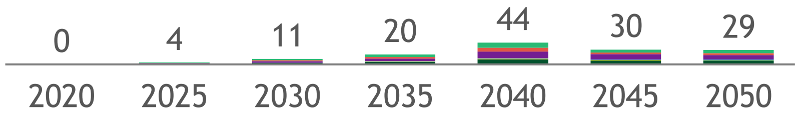


Stated Policies Scenario

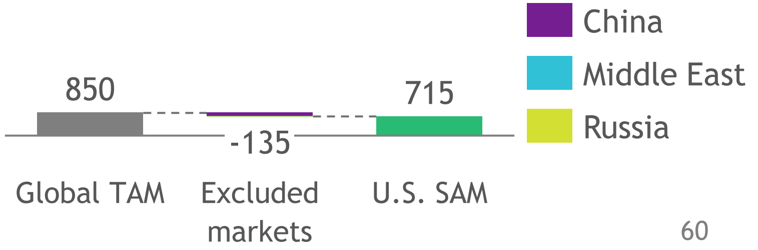
$0.7T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



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[1] Includes both U.S. domestic market and total export SAM

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O&M | O&M presents a small but steadily growing market across scenarios

U.S. domestic market comprises significant portion of SAM across scenarios

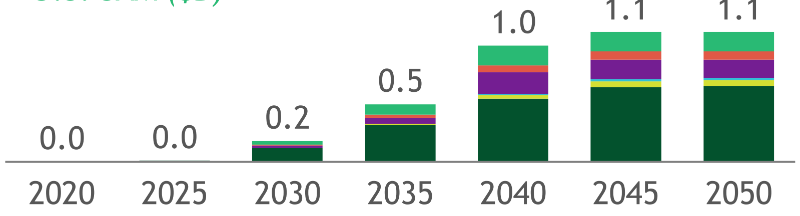
🟩 U.S. 🟥 E.U. 🟪 India 🟦 Japan 🟨 Australia ⬛ Rest of World

Net Zero Emissions Scenario

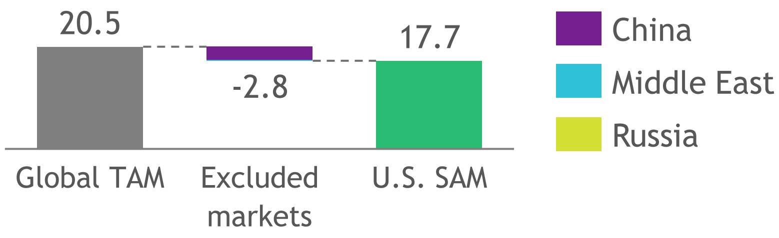
$18B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

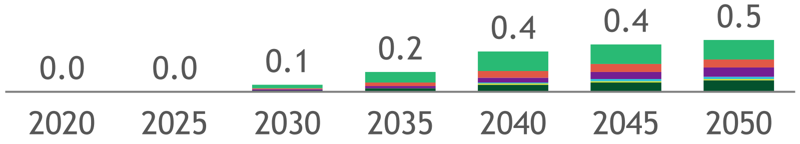


Announced Pledges Scenario

$6B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



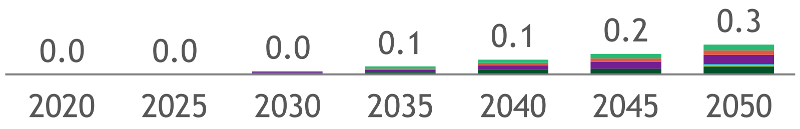
Cumulative Global Market *(2020- 2050, $B)*

Stated Policies Scenario

$3B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

1. Includes both U.S. domestic market and total export TAM

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OEM | U.S.-based companies lead the charge in LDES funding, while Chinese institutes and Japanese and Korean companies lead in research

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw Material Input Availability	N/A	• Not applicable in segment – key inputs are generally widely available (except for vanadium)
☆ **Intellectual Property & Innovation**	Low	• U.S. ranks 4th globally in patent volume in both flow batteries and metal air batteries, significantly behind China and South Korea while slightly trailing Japan • Despite gap in patent volume, the U.S. ranks 3rd in the Global Innovation Index (GII), followed by Korea (5th), China (12th), and Japan (13th) • U.S., S. 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)
Research & Technical Leadership	Low	• The U.S. lags Chinese research paper publications in absolute volume in both flow batteries and metal air batteries, but maintains a strong second place in both categories
Cost Advantage Potential	N/A	• Not applicable in segment – inputs are generally global commodities
Demand / Supply Side Policies	High	• Existing U.S. state-level renewable energy and storage targets (e.g., CA, NY) provide demand-side support for LDES • U.S. DoE Energy Storage Grand Challenge seeks to reduce costs of LDES by 90% by 2030 and encourage domestic manufacturing of LDES technologies. The DoE Long Duration Storage Shot has led to request for $1.2 B in FY 2022 funding
☆ **Market Maturity**	High	• U.S. 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 • Relatively concentrated market with 60 – 70 players creates opportunity for U.S. companies to develop early lead
☆ **Ecosystems and Infrastructure**	High	• U.S. transmission grid creates opportunity for LDES to close transmission gaps to enable high renewable penetration • Mixed set of power market regulations across the U.S. vary in degree of support for LDES, though overall ecosystem creates opportunity to invest in and finance storage projects
Overall ranking	🟩	U.S. found to have **tenuous competitive advantage potential** due to highly mature market relative to others but low activity in the IP / research space

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O&M | U.S.-based companies have received significantly larger amounts of funding than companies abroad, creating potential for competitive advantage

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw Material Input Availability	N/A	• Not applicable in segment – key inputs are generally widely available (except for vanadium)
Intellectual Property & Innovation	Low	• U.S. ranks 3rd globally in patent volume for Battery Mgmt. Systems (BMS), significantly behind both China and S. Korea • Despite gap in patents, the U.S. ranks 3rd in the Global Innovation Index (GII), followed by Korea (5th) and China (12th) • Globally, patent leaders tend to be OEM or advanced manufacturing players (e.g., LG Chem, CATL, Samsung)
Research & Technical Leadership	High	• Although China maintains a slight lead over the U.S., both countries are leaders in BMS-related academic literature, with the U.S. holding more than double the number of papers than the third-highest country, India
Cost Advantage Potential	N/A	• Not applicable in segment – inputs are largely technical talent
Demand / Supply Side Policies	N/A	• Not applicable in segment – little / no relevant types of support for O&M software systems
☆ **Market Maturity**	High	• U.S. companies maintain a significant lead in investment, with investments in U.S.-based companies ~9x that of the second-highest market, Switzerland, and ~14x that of China • Significant M&A activity indicates a dynamic and de-risked market, though presence of large established players abroad (e.g., LG Chem) may present challenges to emerging U.S. companies
Ecosystems and Infrastructure	High	• Large wholesale power, capacity, and ancillary services markets in the U.S. encourage the need for sophisticated BMS software which can accurately predict and capture value in multiple markets
Overall ranking	🟨	U.S. found to have **tenuous competitive advantage potential** due to highly mature market relative to others, however gap in patent activity and a slight lag in research limits competitive potential

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Overview of key assumptions

Assumption	Value	Impact on Calculations	Source
Total battery and H2-fired generation by market	*Varies by year and market*	Based on IEA projections, the combined battery and H2-fired generation capacity makes up the base input for electrochemical LDES calculations. This combined figure represents the total storage capacity across both electrochemical and chemical technology groups, which are the two types which are documented by the IEA. These inputs form the base of the LDES modeling and impact all subsequent values, such as LDES capacity deployed, market value, and potential job growth	IEA 2021 World Energy Outlook
Split of capacity by storage duration required	<8 hrs = ~25% 8 – 24 hrs = ~40% >24 hrs = ~35% *All values reflect 2040+*	These figures are used to split the total storage capacity projections from the IEA into tranches based on estimated durations required. This split is used to inform what proportion of storage would likely be satisfied by Li-ion batteries vs electrochemical LDES (see next row) This split impacts LDES capacity forecasts, which in turn drives market value and job growth	LDES Council[1]
LDES penetration per storage duration	<8 hrs = 0% 8 – 24 hrs = 50% >24 hrs = 100%	These inputs are used to estimate what proportion of storage capacity per tranche is satisfied by LDES vs Li-ion storage. These values are applied to the total storage capacity forecasted per duration tranche to forecast the LDES capacity deployed, which in turn drives market value and job growth	LDES Council;[1] expert input
LDES power and energy capacity cost forecasts	Power capacity: ~$1,920/kW (2025) ~$550/kW (2040+) Energy capacity: ~$16/ kWh (2025) ~$10/kWh (2040+)	These cost estimates are applied to the LDES capacity forecasts to estimate total market value and related job potential per value chain segment	LDES Council[1]

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1. Long Duration Energy Storage Council – Net-zero Power: Long Duration Energy Storage for a Renewable Grid

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EVs

Electric Vehicles | Definition of each segment across value chain

Raw materials	Battery & powertrain manufacturing	Component manufacturing	Software development	OEM	Sales	Charging infrastructure	Aftersales maintenance	Aftersales services
Mining or synthesis, refining, and production of raw materials • Battery minerals (Li, Co, Ni, Mn, Al, Fe, SiC) • Vehicle body/ powertrain (steel, copper, aluminum, rare earths) • Battery EoL recycling	Battery cell manufacture (electrode production, cell assembly & finishing) Battery pack assembly Motor manufacture (e.g., motor winding) Electronic control systems & inverters	Tier 1 (finished parts & assemblies) & 2 (input components) manufacturing of classical components, including interior modules, suspension, body electronics, infotainment & safety systems E/E, ADAS, and AV components Chip & microcontroller production	Tier 1 & OEM development of integrated software stacks to support infotainment, ADAS/AV, data & analytics, car OS, and enablement of aftersales services Out-of-vehicle connected software ecosystem	Vehicle design & development Integration of supplier components & production/assembly operations Manufacturing site creation, including permitting, development, construction & tool-up Financing growth through internal cashflow, equity/bond sales, VC/private investment, and/or partnerships, sometimes with government support Capital investments (tooling, equipment, etc.) for press, body, paint, and assembly processes Skilled production line labor to drive operations	EV unit sales to consumers through traditional wholesaling & franchised dealerships, OEM-owned agency sales centers, or non-dealership D2C sales Consumer purchase financing & leasing	Site selection & ownership Grid connection & electricity delivery Equipment supply, including development & manufacture Insurance & financing Installation, repair, and maintenance of field units Operation, including IT back-end/billing	Traditional after-market support including vehicle servicing, parts sales, and repair	Connected service offerings (OTA software & features, add-on services, data collection & analytics, ADAS, connectivity) Charging support services Mobility-as-a-service, including OEM ride-sharing

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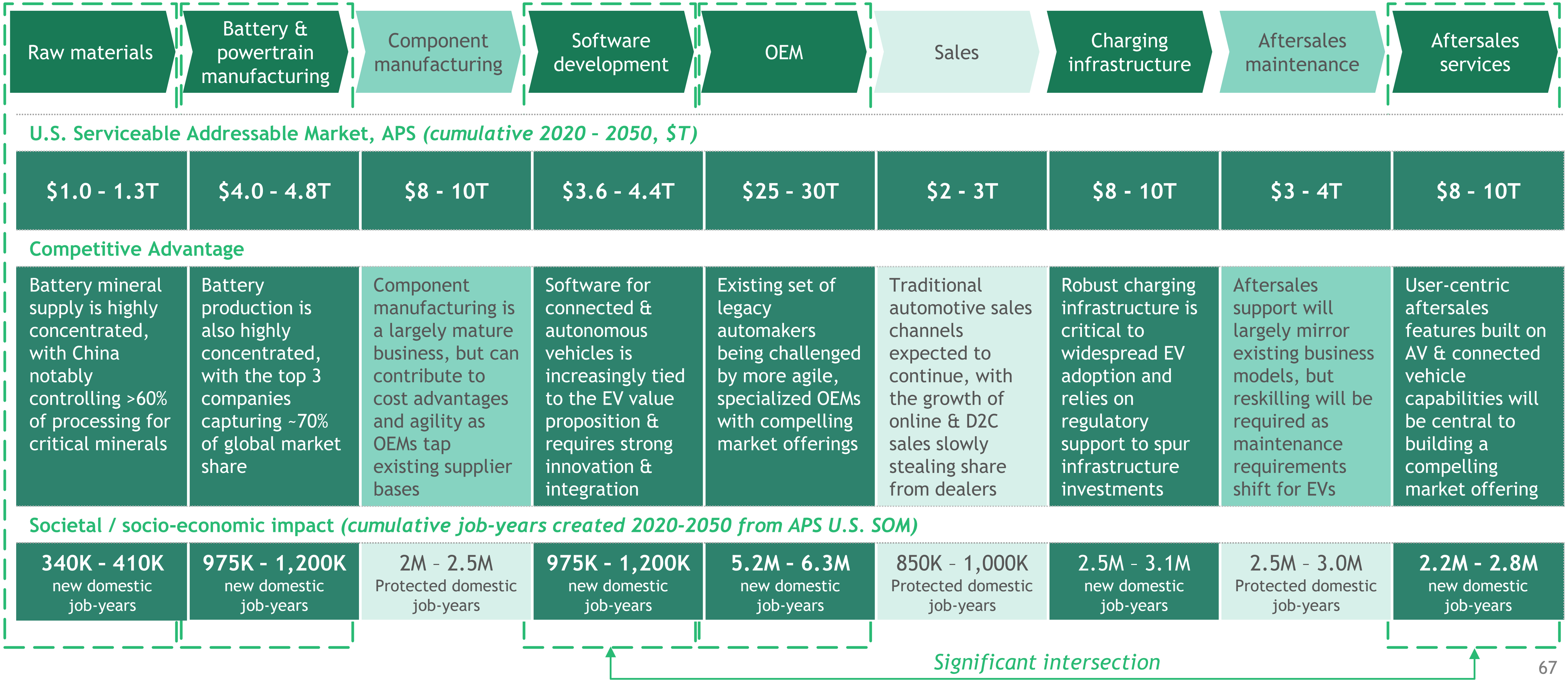
Electric Vehicles | Opportunity to drive advantage by securing raw material & battery production, differentiating OEM & software offerings

Additional analysis in Phase 2

High	Medium	Low	N/A



	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

Significant intersection

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Electric Vehicles | Raw materials

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Key raw materials for EVs include 'legacy' metals such as iron, aluminum, and copper, largely used for the automotive body & propulsion system as well as the extraction & refining of large amounts of minerals for lithium-ion battery production, including lithium, cobalt, graphite, nickel, and manganese

$1.0 - 1.3T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$4 - 5B	$35 - 45B	$45 - 55B	$55 - 75B
Margin (%)	5 - 35%	5 - 35%	5 - 35%	5 - 35%

GLOBAL PLAYERS - COUNTRIES

🟩 Major supplier across multiple raw materials[2]

▨ Major supplier across one raw material[2]

COMPANIES

GanfengLithium

NORILSK NICKEL

BHP

天齐锂业 TIANQI LITHIUM

ALBEMARLE

GLENCORE

VALUE PROPOSITION

Production for critical battery minerals is concentrated in nations such as China or the DRC and poses a point-of-failure risk. Local, reliable access to minerals & processing is a major contributor to upstream supply chain cost competitiveness & stability. Additionally, countries driving innovation in extraction, refining, and recycling can have an outsized impact without controlling mining directly

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	Battery mineral supply is concentrated, with China notably controlling >60% of processing. Much of mining is also owned by China, including ~75% DRC Co, ~50% of Australian Li, 1/3 of Chilean Li, >50% Indonesian Ni	H
Providers/supplier concentration	Mineral production is highly concentrated, with one country dominating ~50%+ of global supply of lithium (Australia) & cobalt (DRC)	H
Existing regulatory env. supportiveness	Companies, particularly in China, are often state-supported, and government focus on beneficial environmental policies & subsidies contribute to domestic growth. Domestic supply may also make EVs more politically attractive. Policy to retain degraded cells within the US may also boost recycling	M
Intellectual Property, technical expertise, and R&D availability	Continued innovation in mineral extraction & refinement as well as battery recycling can drive down cost & increase supply	M
Cost advantage potential	Minerals are globally traded commodities, and access to differentiators such as proximity to source, cheap power, and low-cost labor & operations can boost advantage	L

1. Preliminary estimate, highly variable given metal & shifting commodity prices
2. 2. Wood Mackenzie, J.P. Morgan, IHS Markit, World Steel Association, USGS, Macquarie

Source: BCG Analysis

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Electric Vehicles | Battery & powertrain manufacturing

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Manufacturing of the powertrain, including the battery pack, motor, and electronic control systems, is the critical differentiator in EVs. Electrode production, cell assembly & finishing, motor winding & assembly, and the production of high-current electronic control systems & inverters are central to successfully deploying vehicles with increasing range & performance

$4.0 - 4.8T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$15 - 20	$130 - 140	$160 - 180	$200 - 220
Margin (%)	5 - 10%	5 - 10%	5 - 10%	5 - 10%

GLOBAL PLAYERS - COUNTRIES

🟩 Major battery producer & exporter

🟩 Battery production for domestic use

COMPANIES

Batteries

CATL

Panasonic

LG Chem

SAMSUNG SAMSUNG SDI

BYD

Motors

BOSCH

Continental

MAGNA

Nidec

Source: BCG Analysis

VALUE PROPOSITION

Cost reduction in battery manufacturing is key to EVs. Similarly important is the ability to manufacture extremely safe, reliable batteries at scale, an area with potential for US excellence. Production is concentrated in East Asia and ensuring access to batteries should be a domestic priority. Gov't support & incentives are needed to achieve the scale req'd to compete with cheaper foreign alternatives

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Intellectual Property, technical expertise, and R&D availability	New battery chemistry innovations can drive differentiated products with higher energy density. Strong research investment & programs can advantage countries & companies, but innovations often take time to scale & deliver impact. Manufacturing excellence is required to produce extremely reliable, safe batteries at scale	M
Input material availability & concentration	Proximity to raw materials suppliers and finished products can drive supply chain simplicity and reduce overall costs	M
Providers/supplier concentration	Battery production is highly concentrated, with the top 3 companies (CATL, LG, Panasonic) capturing ~70% of global market share. Motor/ powertrain production is more diversified, but many OEMs still rely on manufacturing in East Asia	H
Cost advantage potential	EV batteries are increasingly becoming cost-differentiated, and access to savings such low-cost labor & operations can boost competitiveness	M
Existing environmental regulatory support	Relevant companies are often state-supported, and gov't focus on permitting & market policies contribute to domestic production capacity growth	L

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Electric Vehicles | Component manufacturing

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

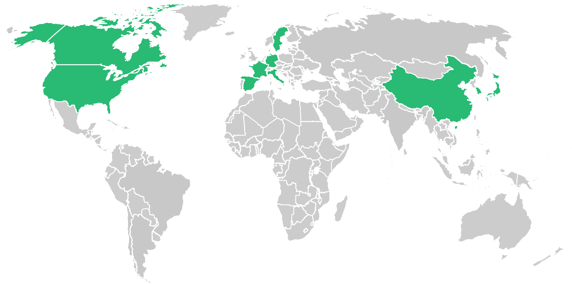
Traditional component manufacturing of standard automotive parts & assemblies applicable to both ICE & EV platforms. Tier 1 (finished parts or assemblies) & 2 (input components) suppliers produce an array of components including seats & control systems, suspension, body electronics & E/E, infotainment & safety systems including chip & microcontroller production

$8 - 10T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$35 - 40	$250 - 270	$350 - 370	$520 - 530
Margin (%)	4 - 6%	4 - 6%	4 - 6%	4 - 6%

GLOBAL PLAYERS - COUNTRIES



🟩 Significant concentration of EV-relevant automotive component suppliers

COMPANIES

LEAR CORPORATION
HYUNDAI
NXP
BOSCH
BRIDGESTONE
Continental
ZF
MAGNA

VALUE PROPOSITION

The ability to produce or procure 'legacy' automotive components cheaply & reliably can serve as a unique differentiator in speed-to-market for EVs due to shared BOMs for major assemblies. OEMs and startups are leveraging the significant existing supply bases in major automotive nations such as the US and Germany to reduce start-up costs and accelerate efforts to scale EVs

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Intellectual Property, technical expertise, and R&D availability	Technology across market segment is highly mature, with minimal movement driven by new IP or R&D innovations	L
Market ecosystem maturity	Market for legacy components is mature with extensive existing supplier & trade relations laying the groundwork for similar players to shift into EVs, but emerging sensor & computing hardware markets still developing	M
Providers/supplier concentration	The landscape of traditional automotive suppliers is well-populated & major players exist in most significant auto-producing nations. Many companies are launching products targeting EVs to stay competitive in a changing market	L
Trained/skilled labor force availability	There is a mix of specialized & trade labor requirements across value chain segment, but extensive production experience and labor pools will help existing players maintain strength	M

Source: BCG Analysis

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Electric Vehicles | Software development

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Development and integration of software stacks to support car systems and features including infotainment, ADAS/AV, performance/maintenance data & analytics, car OS, and enablement of aftersales services. Performed by both Tier 1 suppliers and & in-house OEM teams, depending on system & OEM

$3.6 - 4.4T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$3 - 4	$90 - 100	$170 - 180	$240 - 250
Margin (%)	10 - 20%	10 - 20%	10 - 20%	10 - 20%

GLOBAL PLAYERS - COUNTRIES

🟩 Significant concentration of EV-relevant software developers

COMPANIES

Alphabet
NVIDIA
WAYMO
NIO
XPENG
DENSO
gm

Source: BCG Analysis

VALUE PROPOSITION

Advanced software including connected vehicles and ADAS/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 market segment

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Intellectual Property, technical expertise, and R&D availability	While more legacy systems such as infotainment are mature, there is major innovation across the connected car and autonomous driving landscape. Development in the still-nascent AV space, where the US hosts the notable leaders, has the potential to unlock significant competitive advantage	H
Financing access	Financing today provided by industry & niche players such as VCs & OEM investments for most development in the space	M
Existing environmental regulatory support	Regulatory support is important to create suitable technology testing environments, and to ensure uniform requirements that simplify market entry. Gov't investment is also important to protecting a technical lead amidst foreign initiatives to grow AI/ML & autonomous capabilities, notably in China	M
Trained/skilled labor force availability	Highly specialized programming, AI/ML, and integration engineering skills are required for success. Traditional OEMs are not structured to be agile enough to excel in emerging markets distinct from their current core competencies, and will find transitioning from a legacy mechanical eng. focus to building such teams challenging	H

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Electric Vehicles | OEM

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

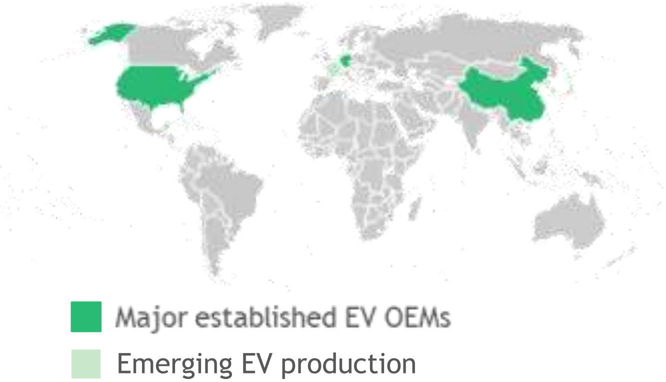
The core EV product is designed & built by the OEM, as it coordinates technical operations, supplier & component integration, as well as facility standup, tooling, training, and production. Robust technical teams and capital investments are required, as OEMs also coordinate financing through cashflow & private/public market fundraising

$25 - 30T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$85 - 90	$860 - 880	$1100 - 1200	$1500 - 1600
Margin (%)	<5%	<5%	<5%	<5%

GLOBAL PLAYERS - COUNTRIES



COMPANIES

Tesla, Volkswagen, SAIC, BYD, Lucid, Arrival, GM, NIO, Rivian, Zoox, Hyundai

VALUE PROPOSITION

Success in EVs relies on a compelling OEM market offering, the ability to manufacture at a competitive price point, and the capacity to rapidly scale to fulfill demand. EV production is the most capital-intensive and technically demanding component of the value chain, dependent on expertise and financing to drive growth, as well as continued manufacturing innovations to cut costs

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Intellectual Property, technical expertise, and R&D availability	While EV technology is rapidly maturing, proprietary battery, electrical control system, and powertrain designs still give OEMs a differentiating competitive advantage. Strong IP & technical teams are required to design a competitive product, and technical differentiation is expected to continue as OEMs compete on range, performance, manufacturing, and features	H
Trained/skilled labor force availability	EVs have lower assembly requirements vs. ICE automobiles, but line labor will need retraining and is still a differentiator in production	M
Existing environmental regulatory support	Government assistance with permitting & regulation, as well as subsidies & incentives for EV purchasing, low-interest loans, and tax benefits, are important growth & fostering emerging OEMs	H
Financing access	Financing in EVs is primarily driven by the OEM themselves, with established legacy players raising funds through cash flow/bond sales, and emerging OEMs relying on venture capital and private equity to scale production in the capital-intensive auto production segment	M
Relevant infrastructure potential	Existing auto manufacturing facilities require retooling to support EV production, but shared processes such as stamping can be directly applied	M

1. Many EV OEMs will not break even until ~2030+, margins will substantially increase over time as market matures
Source: BCG Analysis

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Electric Vehicles | Sales

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

EV new car sales to consumers through traditional wholesaling & franchised dealerships, OEM-owned agency sales centers, or non-dealership D2C sales, including leasing & consumer purchase financing

$2 - 3T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$10 - 15	$150 - 160	$360 - 440	$800 - 900
Margin (%)	<5%	<5%	<5%	<5%

GLOBAL PLAYERS - COUNTRIES | COMPANIES

Not applicable

VALUE PROPOSITION

EVs are poised to accelerate shifts in sales channels away from traditional local dealerships to direct-to-consumer and online business models. This asset-lite model, offering the agility & lower costs of direct sales channels, will be critical to success for many newer EV OEMs as legacy brands struggle to manage large dealership networks.

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Market ecosystem maturity	Car sales today are performed locally, with regional dealership networks performing most new car sales. Maturity of existing sales channels will likely temper adoption curves of emerging D2C & OEM-owned models	L
Providers / supplier concentration	Market is fragmented with no dealerships controlling a major fraction of the market. However, local oligopolies can exist with a small group of sellers dominating regional markets	L
Existing environmental regulatory support	Changing federal & state government regulations or dealer requirements could rapidly accelerate the growth of online and direct-to-consumer car sales, particularly relevant for emerging EV OEMs. Additionally, municipal incentives & assistance transitioning traditional dealerships to EV sales can help support the transition for that sales channel	L

Source: BCG Analysis

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Electric Vehicles | Charging infrastructure

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

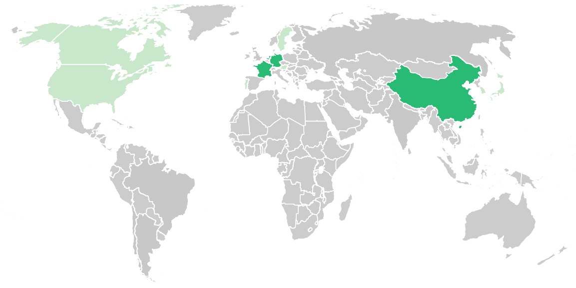
The buildout of both private/in-home and public charging infrastructure is central to enabling the EV transition. Level 3 fast chargers which leverage high voltages (800+ V) to rapidly deliver range will becoming increasingly important as adoption grows, in conjunction secondary enablers such as battery-to-battery systems

$8 - 10T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$15 - 20	$130 - 140	$160 - 180	$200 - 220
Margin (%)	10 - 15%	10 - 15%	10 - 15%	10 - 15%

GLOBAL PLAYERS - COUNTRIES[2]



🟩 Countries with leading charging networks

🟩 Countries with emerging charging networks

COMPANIES

chargepoint

ABB

Tesla

newmotion
A Member of the Shell Group

blink

EVBOX

SIEMENS

VALUE PROPOSITION

The availability of chargers, and in particular public fast chargers, will be a differentiating driver in EV adoption. Both the density and speed of charging networks, as well as the strategic placement of chargers in accessible and high-value locations (e.g., shopping malls), will be crucial. Additionally, this requires both grid preparedness & regulatory support that will differentiate markets

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing environmental regulatory support	Direct funding and incentives from governments can help both rapidly accelerate charging network buildout and drive the grid modernization required to support increased loads. Additionally, regulation of connection standards, including universal ports & plug-and-charge capabilities, would help reduce roadblocks to adoption	H
Relevant infrastructure potential	The robustness & capacity of existing grid connections can be a determining factor in the number of candidate locations for EV chargers. Notably, modern transformers capable of handling the large loads required for fast charging are much more common in the EU and East Asia than in the US, which has a comparatively aging grid	M
Financing access	Funding is still primarily provided through venture & private equity investments, with a combination of public grants & incentives providing additional support	M

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1. Significant variability by region & timeframe, steady-state margin expected to be ~10% 2. Lease Fetcher, based on both total charger count & ratio of chargers to EV population
Source: BCG Analysis

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Electric Vehicles | Aftersales maintenance

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Classical aftermarket support for automobiles includes both ongoing & acute (collision) maintenance, which are serviced by a large network of OEM-affiliated and independent auto repair shops. Aftermarket maintenance also serves as a large source of OEM & supplier revenue for replacement parts and consumables

$3 - 4T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$1 - 5	$70 - 80	$180 - 220	$270 - 330
Margin (%)	3 - 10%	3 - 10%	3 - 10%	3 - 10%

GLOBAL PLAYERS - COUNTRIES[1] COMPANIES

Not applicable

VALUE PROPOSITION

The classic aftermarket maintenance segment will experience a major transformation as EV adoption increases, due to the lower ongoing maintenance requirements of electric powertrains as well as the significant reskilling required to adapt labor pools to the care of new components & systems, including advanced sensor & computing suites. The ability to smoothly execute this transition while maintaining a sufficient aftermarket repair capacity will be important, and likely will be largely supported by OEMs

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Providers / supplier concentration	The current aftermarket maintenance segment is highly fragmented with a diverse landscape of independent repair shops	L
Trained/skilled labor force availability	Current automotive maintenance labor force will require significant retraining to give it the skills to work on EVs, including ability to work with battery-electric powertrains, sensitive sensors & chips, and new body designs and materials	M

---

1. Lease Fetcher, based on both total charger count & ratio of chargers to EV population
Source: BCG Analysis

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Electric Vehicles | Aftersales services

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Aftersales services will rapidly expand with the adoption of EVs and parallel growth of connected & autonomous fleets. Vehicle-to-everything (V2X) smart features, vehicle-to-vehicle (V2V) capabilities, fleet connectivity/analytics, car apps & services, as well as autonomous & assisted driving subscriptions & ride-hailing are expected to grow as the segment matures

$8 - 10T
Cumulative APS
US SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	$1 - 2	$160 - 170	$440 - 450	$550 - 650
Margin (%)	5 - 10%	5 - 10%	5 - 10%	5 - 10%

GLOBAL PLAYERS - COUNTRIES[1]

🟩 Significant concentration of leading EV aftersales service developers/providers

COMPANIES

ERICSSON
WAYMO
ZOOX
wejo
cruise
BMW ConnectedDrive
otonomo

VALUE PROPOSITION

The growth of these services is closely tied to the overall EV expansion as customers expect increasingly connected features from their vehicles. Success in this segment is directly reliant on the software development and, critically, integration capabilities of the OEM & suppliers/partners, and will in turn act as a defining market differentiator amongst EVs

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Intellectual Property, technical expertise, and R&D availability	While legacy systems such as infotainment have matured, there is major innovation across the connected car and autonomous driving landscape. Development in the AV space, where the US hosts the notable leaders, has the potential to unlock significant competitive advantage, and early leaders will experience advantages in building consumer trust & securing OEM partnerships	H
Financing access	Financing today provided primarily by industry & niche players such as VCs & OEM investments	M
Existing environmental regulatory support	Regulatory support is important to create suitable technology testing environments, and to ensure uniform requirements that simplify market entry. Gov't investment is also important to protecting a technical lead amidst foreign initiatives to grow AI/ML & autonomous capabilities, notably in China	M
Trained/skilled labor force availability	Specialized programming, AI/ML, and integration engineering skills are required for success. Traditional OEMs may find transitioning from the legacy focus on mechanical engineering to building such teams challenging	H

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1. Lease Fetcher, based on both total charger count & ratio of chargers to EV population
Source: BCG Analysis

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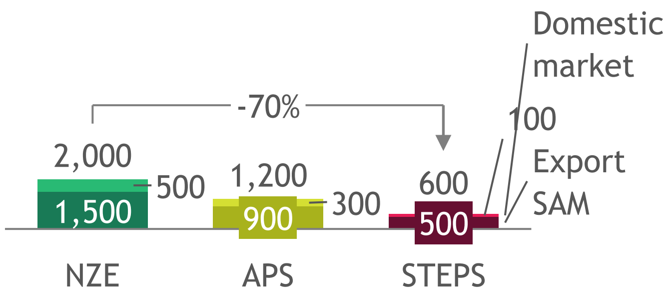
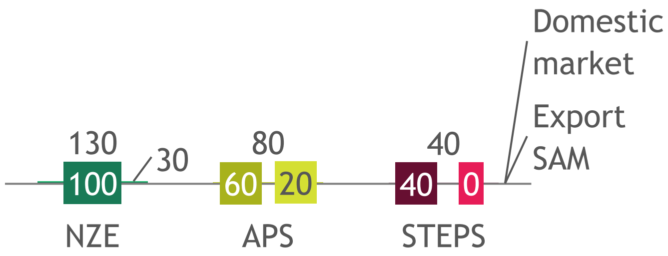
Large SAM across market segments and scenarios reflective of massive global automotive demand and significant private & public momentum in electrification

Raw materials

U.S. Serviceable Addressable Market (SAM)
(2020 - 2050, $B)



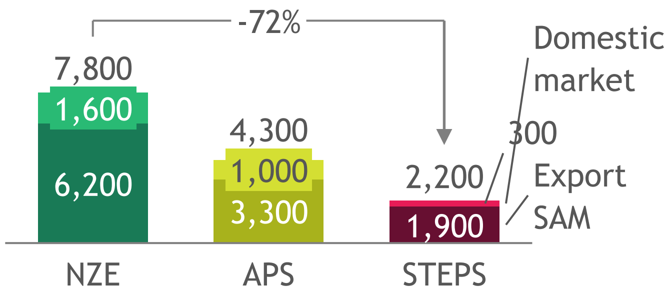
U.S. Serviceable Addressable Market Margin Pools
(2020 - 2050, $B)



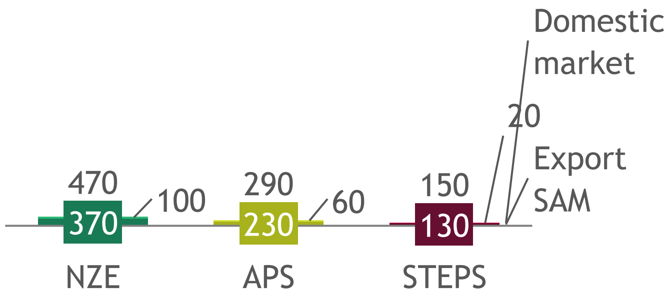
~5 - 35%[1] Est. gross average margin

Battery & powertrain manufacturing

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



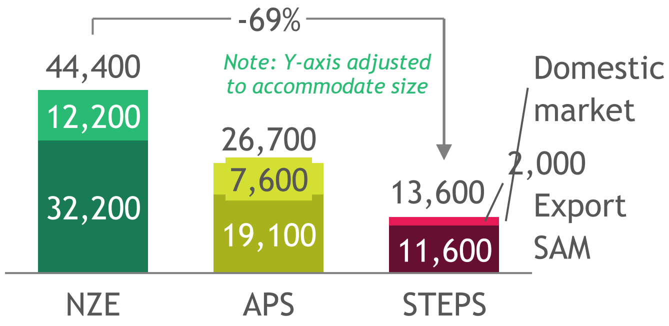
U.S. Serviceable Addressable Market Margin Pools
(2020 - 2050, $B)



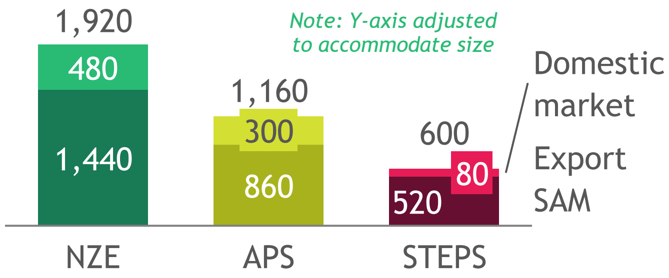
~6 - 9% Est. gross average margin

OEM

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



U.S. Serviceable Addressable Market Margin Pools
(2020 - 2050, $B)



~ 0 - 4% Est. gross average margin

1. Broad range due to variation across minerals and high potential & experienced volatility in commodity metals pricing. ~6% average margin used for baseline analysis
Source: BCG analysis

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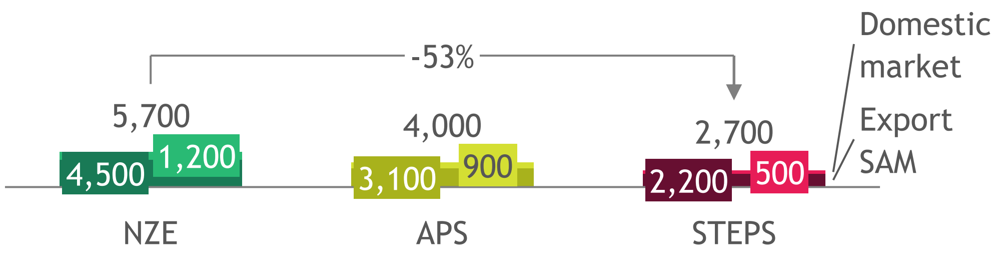
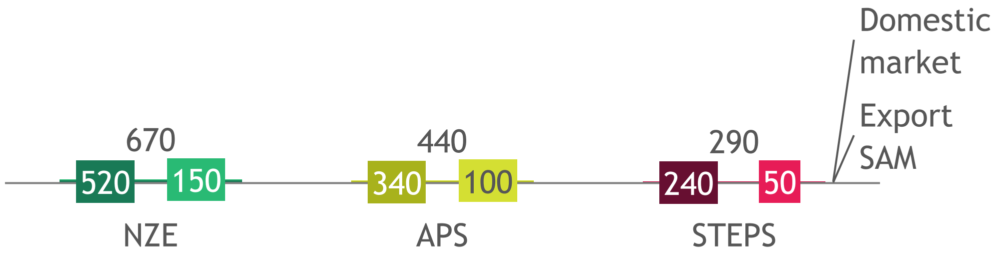
Large SAM across market segments reflective of massive global automotive demand and significant private & public momentum in electrification

Software

U.S. Serviceable Addressable Market (SAM)
(2020 – 2050, $B)



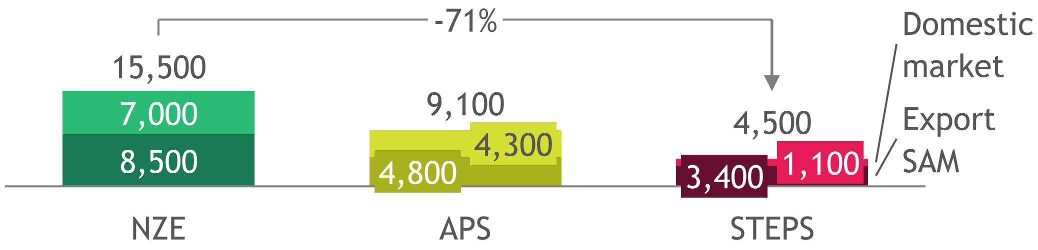
U.S. Serviceable Addressable Market Margin Pools
(2020 – 2050, $B)



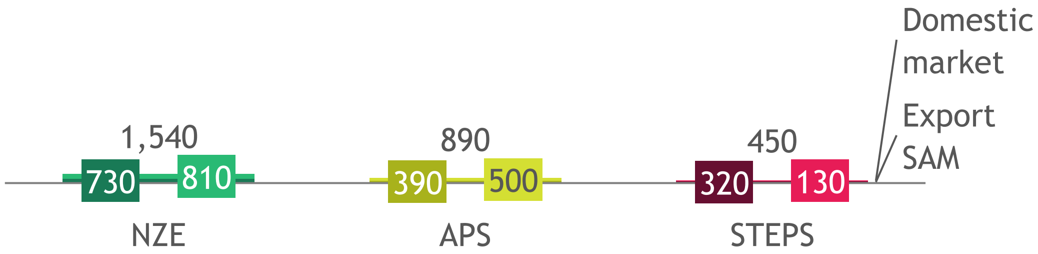
~15% Est. gross average margin

Aftersales services

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



U.S. Serviceable Addressable Market Margin Pools
(2020 - 2050, $B)



~9 - 10% Est. gross average margin

1. Broad range due to variation across minerals and high potential & experienced volatility in commodity metals pricing. ~6% average margin used for baseline analysis
Source: BCG analysis

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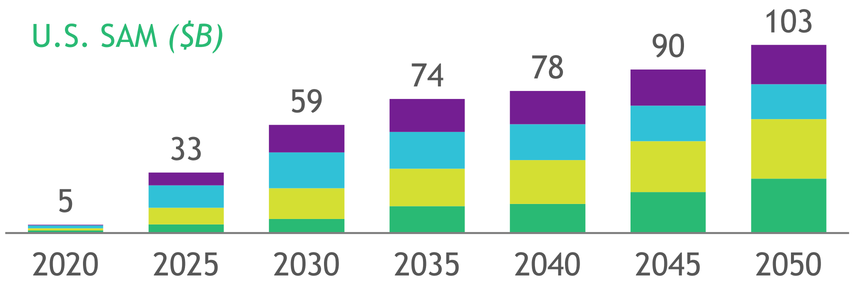
Raw materials | Large ~3x delta in global battery mineral TAM across scenarios, China expected to limit foreign-controlled imports

Net Zero Emissions Scenario

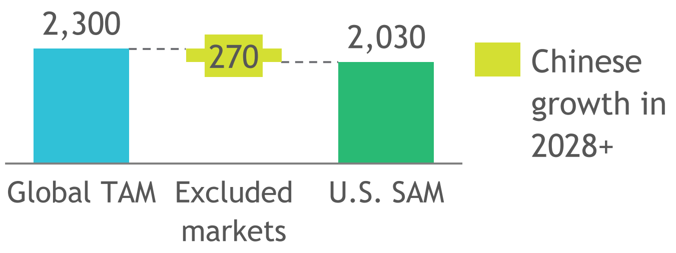
$2.0T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 – 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

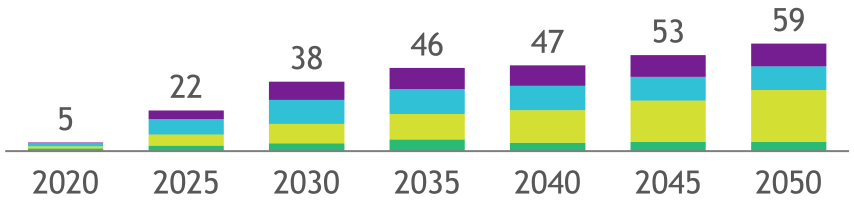


Announced Pledges Scenario

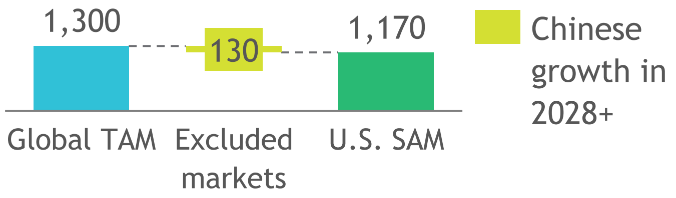
$1.2T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 – 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

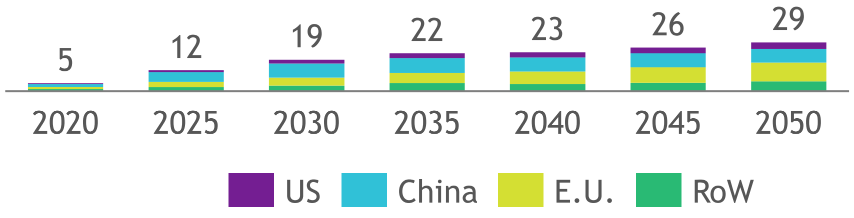


Stated Policies Scenario

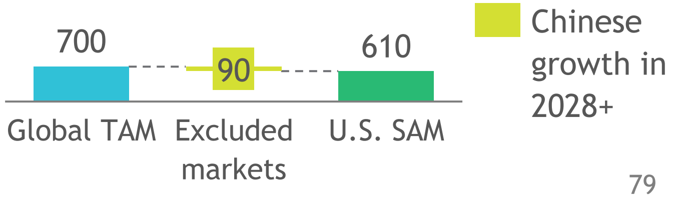
$610B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 – 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*



1. Includes both U.S. domestic market and total export SAM

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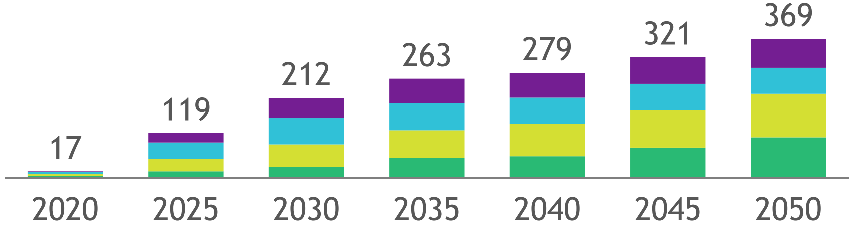
Battery & powertrain manufacturing | China ~40% global near-term TAM in STEPS due to ambitious policies, more variability in US, E.U.

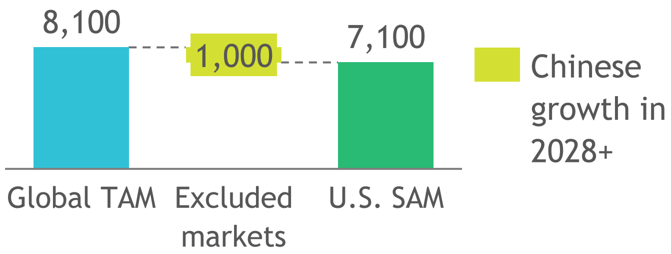
Net Zero Emissions Scenario

$7.1T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*



U.S. SAM *($B)*

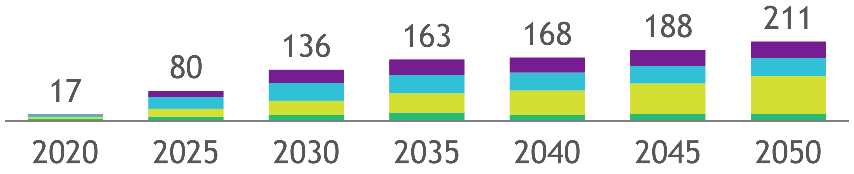


Cumulative Global Market *(2020-2050, $B)*

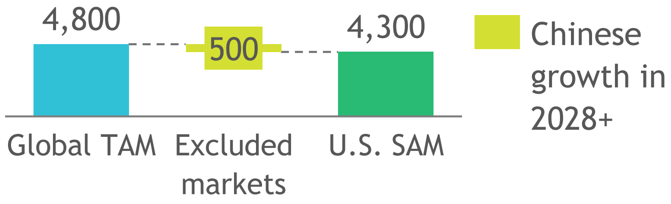
Announced Pledges Scenario

$4.3T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*



U.S. SAM *($B)*

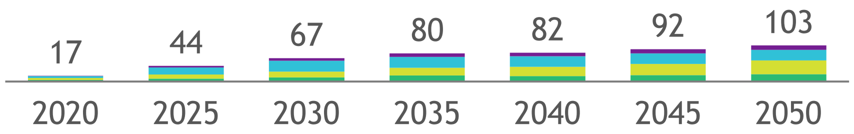


Cumulative Global Market *(2020-2050, $B)*

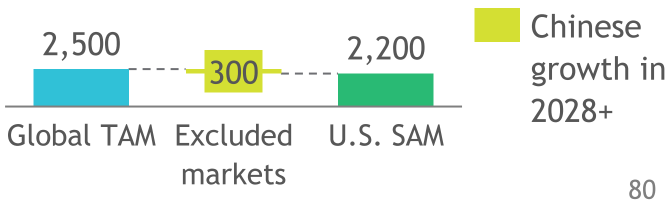
Stated Policies Scenario

$2.2T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*



U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

🟪 US 🟦 China 🟨 E.U. 🟩 RoW

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[1] Includes both U.S. domestic market and total export SAM

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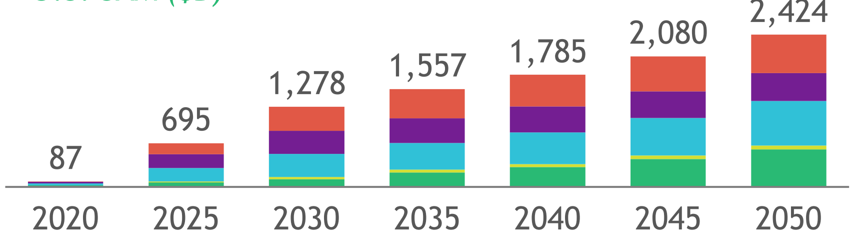
OEM | Largest value chain segment across scenarios with lowest cumulative TAM estimate of $14T in STEPS

Net Zero Emissions Scenario

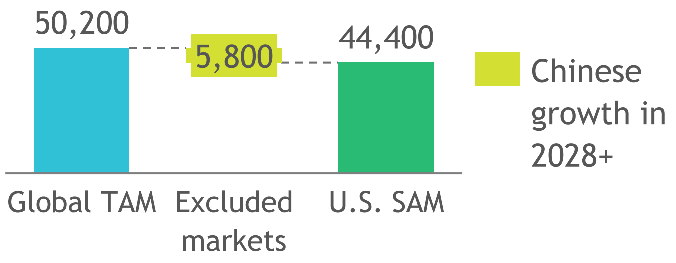
$44T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

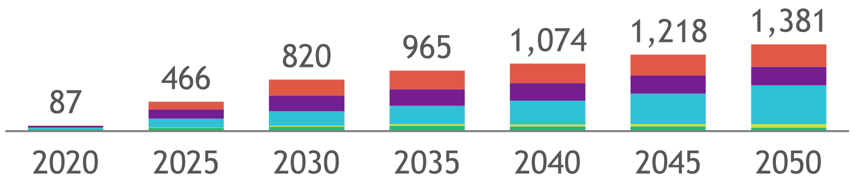


Announced Pledges Scenario

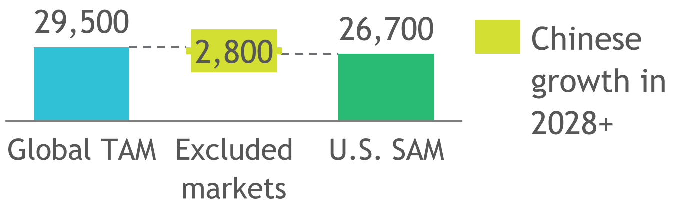
$27T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

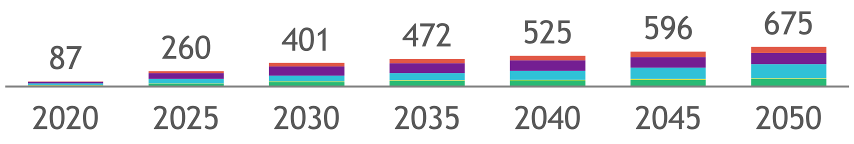


Stated Policies Scenario

$14T

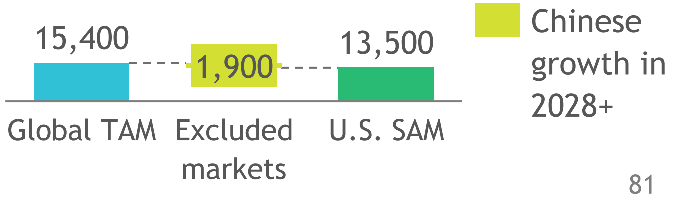
Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



🟥 US 🟪 China 🟦 E.U. 🟨 Canada 🟩 RoW

Cumulative Global Market *(2020-2050, $B)*



[1] Includes both U.S. domestic market and total export SAM

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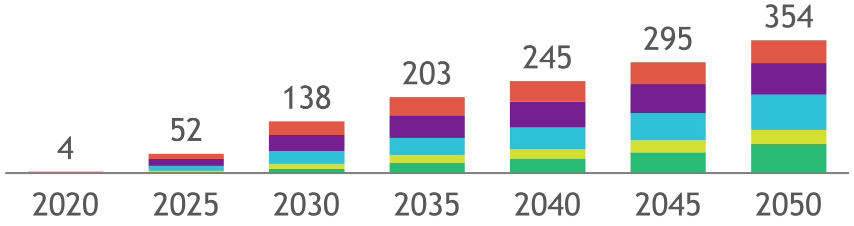
Software development | Software market experiences rapid growth after ~2028 as applications reach commercial viability

Net Zero Emissions Scenario

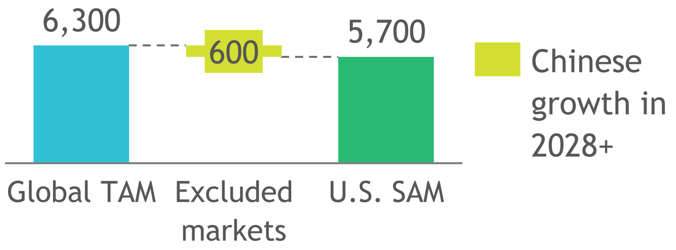
$5.7T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 – 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

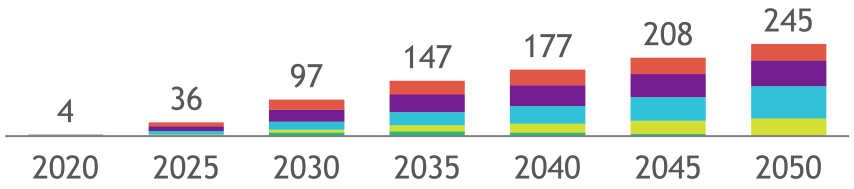


Announced Pledges Scenario

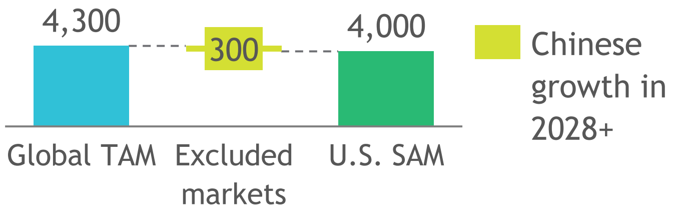
$4.0T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 – 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

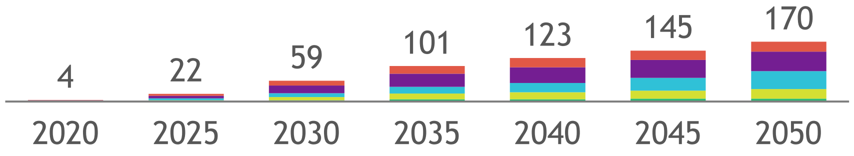


Stated Policies Scenario

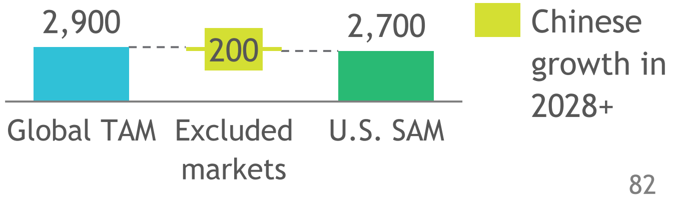
$2.7T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 – 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*



🟥 US 🟪 China 🟦 E.U. 🟨 Japan 🟩 RoW

[1] Includes both U.S. domestic market and total export SAM

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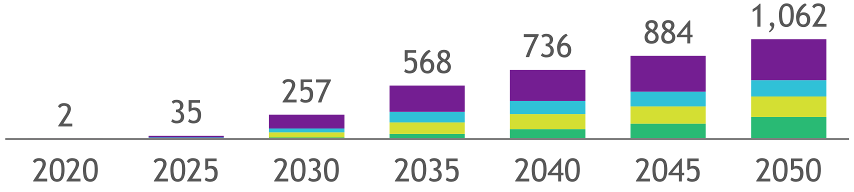
Aftersales services | Rapid growth after ~2030 as AV, connected vehicle applications become integrated with EV ecosystem

Net Zero Emissions Scenario

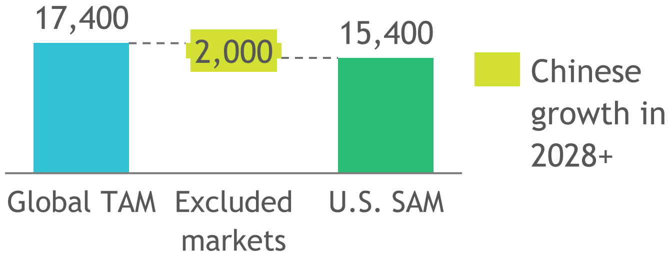
$15T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

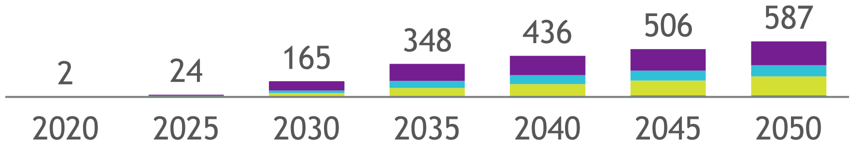


Announced Pledges Scenario

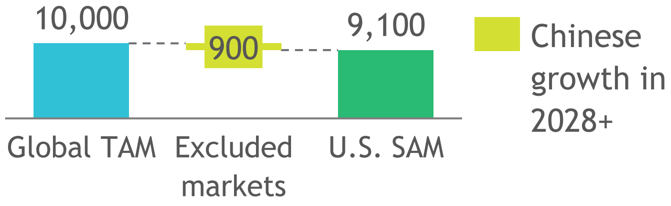
$9.1T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

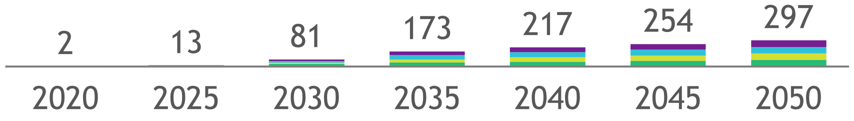


Stated Policies Scenario

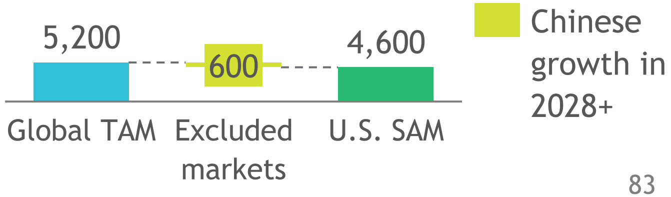
$4.6T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*



🟪 US 🟦 China 🟨 E.U. 🟩 RoW

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[1] Includes both U.S. domestic market and total export SAM

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Raw Materials | U.S. behind in raw material innovation and investment, with highly limited domestic extraction or processing activity

☆ = *Key dimension*

	Areas for Competitive Advantage	Current ranking	Summary analysis
☆	**Raw material availability**	High	- U.S. has significant lithium brine reserves in the Southwestern U.S. as well as the necessary extraction technologies. Additionally, the U.S. has small amounts of known cobalt and nickel reserves but limited existing extraction operations across all minerals. Canada also hosts reserves that could be leveraged to build the overall NA supply chain
	Intellectual Property & innovation	Low	- Patent volume since 2015 in raw material mining, extraction, and processing extremely small relative to other major EV innovators, behind China (+1070% vs. U.S.), Japan (+170%), and South Korea (+80%). Overall patent volume is just ~9% of Chinese patenting, and only one U.S. company is within the top 15 high patent-volume entities globally
	Research & technical leadership	Low	- Similar to the overall patent landscape, Chinese researchers publish raw materials-related science at ~5x the rate of U.S. researchers. Additionally, a minimal gap in overall citations/paper between the two countries suggest Chinese research is higher-quality than in other segments, and the top 20 institutions in the field are almost exclusively located in China
	Low operational costs	Low	- Labor is a significant portion of cost in this segment, U.S. labor costs are above-average globally and significantly higher than other mineral supply regions such as South America, East & Southeast Asia, and Africa. However, opportunity to labor share down through operational innovations & automation
	Demand / supply side policy	High	- Despite a delay in policy surrounding production & procurement of critical battery minerals within the U.S., the Biden Administration's recent invocation of the Defense Production Act is a significant step in this direction. While not strictly a demand-side policy, it will help provide funding and guarantee a market for companies within the U.S. - $2.9B allocated in IIJA to boost domestic battery production, including mineral processing, but limited demand-side support
	Relative domestic market maturity	Low	- U.S. investments are notably small in this space, totaling just ~7% of China's private sector investment in the industry since 2017 and 1/3 of Australia's. Combined with major public support in competing countries, U.S. nascent in raw materials market
☆	**Regulatory environment & existing infrastructure**	Low	- Non-uniform and often stringent environmental policy are major inhibitors of new mining/extraction site startup, with disparate state restrictions combining with a slow permitting policy to stimy new initiatives - Lack of uniform federal guidance or oversight has resulted in local protests often driving indefinite delays at proposed sites, 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
	Overall ranking	🟨	U.S. well behind today with minimal mining operations and limited research, IP, or investment in the space

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Battery & Powertrain Manufacturing | U.S. has skilled workforce, upstream IP and limited policy support, but falling behind on investments & downstream IP

☆ = *Key dimension*

	Areas for Competitive Advantage	Current ranking	Summary analysis
	Raw material availability	N/A	• Not applicable in segment
☆	**Intellectual Property & innovation**	Low	• U.S. 4th globally in patent volume in EV batteries behind China (+175% vs. U.S.), Japan (+200%), and South Korea (+170%) – South Korea rapidly expanding patent volume as market leaders including LG Chem, Samsung invest heavily in research and South Korea broadly climbs into the top 5 countries on the Global Innovation Index • Domestic patent leaders skew upstream towards battery materials and novel battery chemistry research vs. foreign manufacturers that focus more on production innovations – The manufacturing complexity of EV batteries & powertrains drives a steep learning curve, and novel chemistries can have major impacts on reliability, safety, and cost, making IP the most impactful area in this segment
☆	**Research & technical leadership**	High	• China's literature publication rate for EV battery research is over 2X the U.S. – Average quality of those papers is notably lower, with an average 29 citations vs. 52 for U.S. publications, suggesting the leadership of U.S. work is comparatively high – Additionally, U.S. often closer to the cutting edge, partially reflected in the Global Innovation Index ranking which puts U.S. ahead of all competing countries (U.S. #3, vs. Korea at #5, China at #12, Japan at #13)
	Low operational costs	Low	• Although labor is a comparatively small portion of cost in this segment, U.S. labor costs are above-average for manufacturing globally, and significantly higher than all major manufacturing regions except the EU – Largely offset by lower energy costs within U.S./Canada, but additional imbalance remains driven by higher scrap rates, cost of capital, and lack of materials procurement scale today
	Demand / supply side policy	High	• $2.9B allocated in IIJA to boost domestic battery industry, including cell & pack manufacturing, although limited demand-side support
	Relative domestic market maturity	Low	• Chinese investments outpace U.S. by 70% in EV batteries over past 4 years as Chinese manufacturers rapidly scale to control 40%+ of the market
☆	**Regulatory environment & existing infrastructure**	Low	• 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
	Overall ranking	🟩	U.S. well behind today in at-scale production but continues to hold strong IP presence, particularly in battery chemistry

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OEM | Strong U.S. OEM labor force & market ecosystem, but manufacturers behind in IP innovation as Asian & European manufacturers lead in automation

☆ = *Key dimension*

	Areas for Competitive Advantage	Current ranking	Summary analysis
	Raw material availability	N/A	• Not applicable in segment
☆	**Intellectual Property & innovation**	Low	• U.S. patent volume in OEM innovations 5th globally, behind China (+200% vs. U.S.), South Korea (+190%), Japan (+40%), and Germany (+25%) as automakers in those regions invest heavily in EV transition • Toyota, Hyundai the notable leaders in 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
☆	**Research & technical leadership**	High	• U.S. in second place to China in overall literature volume but has significantly higher citations/publication to make it an overall leader in cumulative impact, with DoE and University of Michigan key centers for U.S. OEM-related research • Strong traditional automaker supply base & accompanying workforce that will be powerful in EV transition
	Low operational costs	Low	• U.S. labor costs are comparatively high compared to some automaking regions such as East Asia, but innovations in automation and manufacturing operations continue to drive labor share of cost down in U.S., making overall production costs competitive
☆	**Demand / supply side policy**	High	• Both Federal and State governments have implemented a varying set of EV purchase incentives, including the Federal EV Tax Credit, which have helped to drive EV adoption • Notably however, the investment size is outpaced by similar policies in China, which allocated ~$6B U.S.D in the 2022 fiscal year budget for NEV purchase subsidies. New proposed incentives by the Biden Administration would close this gap
	Relative domestic market maturity	Low	• Chinese investments outpace U.S. by 50% in EV OEM over past 4 years as diverse Chinese manufacturers rapidly scale to meet domestic market demand, but the two countries are notable leaders, with the U.S. outpacing the next nearest nations of Sweden, Germany, and India in investment by 7-11X
☆	**Regulatory environment & existing infrastructure**	High	• Strong legacy infrastructure, policy, and market structure in place to support automakers
	Overall ranking	🟩	U.S. has good OEM environment today, but no clear leadership in EVs and must work to maintain positioning

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Software & aftersales services | U.S. the market leader with dominant IP and investment, should work to ensure policy supports continued deployments

☆ = *Key dimension*

Areas for Competitive Advantage	Current ranking	Summary analysis
Raw material availability	N/A	• Not applicable in segment
☆ **Intellectual Property & innovation**	High	• 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 • Diverse ecosystem of players within U.S. across 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 & technical leadership**	High	• Despite slightly lower publication volume than China putting the U.S. in 2nd in overall literature production, U.S. researchers garner the most total citations globally due to their comparatively higher-impact papers, suggesting the U.S. research ecosystem is a leader in the AI, ML, sensor, and machine vision technologies underlying autonomous driving
Low operational costs	Low	• U.S. software & engineering talent highest-ranked globally in per-head costs, but low overall cost structure and high scalability of software development blunts impact on margin pools
Demand / supply side policy	Low	• Extremely limited public financial support for AV product development or commercialization, including for upstream AI/ML technology relative to competing nations such as China beyond small-scale grants
☆ **Relative domestic market maturity**	High	• 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 • However, VC investment within Asia Pacific region growing at higher rate than North America as shown in the Global Innovation Index, reflecting accelerating investment in emerging technologies within the block
Regulatory environment & existing infrastructure	High	• Limited AV policy guidance at the federal level and momentum amongst relevant agencies to accelerate policies in the space (e.g., NHTSA) • Some state and local-level domains that enable testing & deployment • While some countries including China have provided guidelines for AV deployment, no clear leader in this segment
Overall ranking	🟩	U.S. has strong leadership in advanced automotive software ecosystem. With both innovation and investment leadership, the domestic market possesses the strongest base of current commercial players

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Overview of key assumptions

Assumptions	Value	Impact on modeling	Source
Projected annual new vehicle sales, by region, globally	*Varies by year*	Significant changes in vehicle ownership models or greater than expected macroeconomic growth/downturns could significantly impact global vehicle sales and concurrently change market size across all segments proportionally.	*IHS Markit automotive industry analysis, 2020-2040*
Vehicle/component cost breakdown, and expected penetration at component level	*Varies by year*	Breakdown of value across vehicle components is generally based on historical values and could shift as certain components drive further down the cost curve, reducing respective segment market sizes. Significant new costs, such as advanced sensors, may also additionally impact value breakdown.	*BCG Unit Economic Model, 2021* *Bank of America "Who Makes the Car" report, 2021*
CAGR in 2039-2040 across value pool segments will continue through 2050	*N/A*	Any significant plateau or increase in penetration rates could shift the late-year market projections, respectively.	*N/A*
% BEV powertrain cost attributed to battery	~70%	This % is the direct basis for the raw material segment market size, and significant fluctuations in raw materials prices or changes in dominant battery chemistry could cause this value to shift.	Industry expert interviews König et. al., World Electric Vehicle Journal, 2021
% BEV battery cost attributed to raw materials & minerals	~40%	This % is the direct basis for the raw material segment market size, and significant fluctuations in raw materials prices, battery production processes/economics, or changes in dominant battery chemistry could cause this value to shift.	Industry expert interviews Wentker et. al., Energies, 2019 Bloomberg NEF

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Low-carbon Hydrogen

Low-carbon Hydrogen | Definition of each segment across value chain

	Raw materials	OEM	Project Development	Financing	EPC	Energy Inputs	Operations/ Maintenance	Transport & Storage	Offtake	Support Services
Green	Electrolyser critical materials (e.g., Pt, Ir, Ni, Gd, Zr, Co) Electrolyser stack components (e.g., bipolar plates, membrane, sealings, frames, porous transport layer)	Electrolyser, compressor, water purification and rectifier	Financing for project and long-term offtaker contracts Significant renewable energy procurement Current ecosystem largely made up by energy developers	Financing for low-carbon hydrogen involves securing a capital stack for large-scale projects and providing research funding into nascent electrolyser, reformation and transport technologies.	Engineering, procurement & construction (outsourced or inhouse) • Electrolyser stack and systems construction • Supply chain management • Contractor mgmt. • System testing	Renewable energy	Electrolyser maintenance (e.g., replacing membranes, fighting corrosion) Management of ongoing operations Electrolyser monitoring and upkeep	Conversion (e.g., liquefaction, ammonia/methanol synthesis, hydrogenation) Compression for transport (largely done via positive displacement or centrifugal compressors) Salt cavern, pressurized/cryogenic tank, and materials storage Gaseous tube trailers, liquid tanker, pipeline and chemical hydrogen transport Final delivery of hydrogen to offtaker	End-use cases for hydrogen in energy and chemical production Feedstock for industrial production (e.g., refining, ammonia, cement/steel) Transport, especially for long-distance vehicles Fuel Cells as feedstock for multitude applications (EVs, houses, and portable power) Markets for solid-carbon byproduct from pyrolysis (e.g., soil improver, input for tire manufacturing)	Auxiliary markets created to support hydrogen deployment and uptake • Hydrogen energy consultant • Green Hydrogen certification (e.g., CertifHy)
Blue	Metals for reformer tubes (e.g., Cr, Ni, Fe)	Reformer (ATR/SMR) and CCUS technologies	Current ecosystem mostly consists of large O&G players		• Reformer (ATS/SMR) • CCUS technology	Natural gas resources	CCUS monitoring and upkeep			
Turquoise	Amine-based solvents for chemical absorption CCS Solid surfaces for adsorption (e.g., activated carbon, alumina, metallic oxides), liquid solvents for absorption (e.g., Selexol, Rectisol)	Catalytic pyrolysis for turquoise H_2 involves molten metal or gas reactors				Natural gas and biomass resources for pyrolysis				

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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 (*peak job-years created 2020 - 2050*)	**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

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Low-carbon Hydrogen | Raw Materials & Inputs

High	Medium	Low	N/A

Description of technology value segment

Raw materials & inputs for green hydrogen include mining and processing critical electrolyser materials such as Platinum, Iridium, and Nickel. Reformer raw materials include metals for pipes (e.g., Cr, Ni, Fe). CCS materials include amine-based solvents for chemical absorption, solid surfaces for physical adsorption, and liquid solvents for physical absorption.

$310 - 480B
Cumulative APS U.S. SAM
($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	4 - 5	15 - 20	10 - 15
Margin (%)	5 - 10%	5 - 10%	5 - 10%	5 - 10%

Global players - countries

🟩 Raw materials being mined
China (~70%)
South Africa (~30%)
🟩 Raw materials in country but not mined

🟦 Significant natural gas reserves (>5% world share)

Russia (~50%)	Qatar (~20%)
Iran(~20%)	US (~10%)

Companies

Mining
AngloAmerican
KINROSS

Oil & Gas
EDF
Shell
ENGIE
e.on

Value proposition

While Raw Materials & Inputs may at first appear attractive due to its large market size, the very high global concentration of critical electrolyser materials lessens the opportunity to play in this space and develop a competitive advantage for players without direct access to these resources. In addition, the ability to purchase these raw materials at global commodity prices further decreases the attractiveness of this segment for subsequent deep-dive.

Evaluation

Market	Competitive Advantage	Societal Impact

Competitive advantages

Input material availability & concentration	Availability of critical electrolyser materials (e.g., Pt, Co, Ni, Ir) is concentrated with China holding >95% of global supply of Gd, Zr, La, Ce, and Y2[2]	H

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1. ituc global rights index (2018); 2. IRENA Green Hydrogen Cost 2020
Source: eia.gov; BCG Analysis

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Low-carbon Hydrogen | OEM

High | Medium | Low | N/A

Description of technology value segment

OEM for green hydrogen includes R&D into and manufacturing of electrolysers, compressors, water purification and supporting systems. OEM for blue hydrogen involves reformer (SMR or ATR) and CCUS technologies R&D and manufacturing. Pyrolysis[5] for turquoise H_2 involves molten metal or gas reactors.

Value proposition

OEM presents an opportunity to build competitive advantage in a segment with large potential cumulative market value. Electrolyser manufacturers are relatively small and highly concentrated, creating space for new entrants. To grow to industrial-scale projects requires direct government funding. There is a range of export potential including the IP, hydrogen, ammonia or methanol, and electrolyser and reformers. However, there is risk of commoditization and competition on costs, especially from Chinese electrolysers

$460 - 560B
Cumulative APS U.S. SAM
($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	5 - 10	20 – 30	15 - 20
Margin (%)	10 - 20%	10 - 20%	10 - 20%	10 - 20%

Evaluation

Market	Competitive Advantage	Societal Impact

Competitive advantages

Existing regulatory env.	In order to scale to industrial-sized electrolysers and make green hydrogen cost-competitive, direct financial support in the form of subsidies and carbon taxes is necessary to lower green premium and fund further research efforts	H
Providers/supplier concentration	OEM market today is concentrated, with top 5 players controlling 40-60% of the market. Potential disruption arising from Chinese OEMs producing electrolysers at ~1/3rd current market rate[4]	M
IP & relevant technical expertise availability	ATR has high potential (84% vs. 74% efficiency, 98% vs. 90% CO_2 capture rates for ATR and SMR respectively[1]) and has defendable IP No electrolysers are made without rare metals. High potential and defendable IP if technology can improve to be made with different or no rare metals (e.g., Pl and Ir, used in PEM, are two of the scarcest, most energy-intensive and emission-intensive metals[3]) Industrial-scale electrolyser technology is nascent, but has high potential and defendable IP (e.g., Plant balancing makes up 55% of system costs for electrolyser plants[2])	H
	Catalytic and plasma pyrolysis for turquoise H_2 only at a TRL of 7. Medium potential to improve catalyst mechanical stability and improve output purity.	M
Trained/skilled labor force availability	Highly specialized skills required for R&D efforts. Opportunity to build advantage, as labor force has limited experience in manufacturing industrial-scale plants/electrolysers given market immaturity.	H

Global players - countries

🟩 Industrial-scale (>10 MW) electrolysers deployed
China (~50% of market)
Norway (~25% of market)
Japan (~25% of market)
🟩 Piloting industrial-scale projects

Companies

Electrolyser

thyssenkrupp, McPhy, ITM POWER, AIR PRODUCTS, AsahiKASEI, nel, John Cockerill

SMR/ATR

Linde, Air Liquide, BALLARD

Catalytic Pyrolysis

HazerGroup, Honeywell UOP

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1. Uk.gov – Hydrogen production costs 2021; 2. iea The Future of Hydrogen; 3. IEA; 4. rechargenews; 5. Systems for Catalytic Pyrolysis
Source: Asahi-Kasei; Shell; IEA Hydrogen Projects Database (2021); Global Data; Expert Interviews; BCG Analysis

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Low-carbon Hydrogen | Project Development

High	Medium	Low	N/A

Description of technology value segment

Project development for green hydrogen largely involves securing financing, long-term offtaker contracts, and procuring significant renewable energy inputs. .

Value proposition

Opportunity in Project Development is driven by the high-level skillset required to pull together and successfully execute nascent, large-scale, low-carbon hydrogen projects. Furthermore, a global export potential is evolving as domestic energy providers are internally building the skills for developing low-carbon hydrogen projects and capitalizing on the early-mover advantage presenting itself in this segment.

$105 - 130B
Cumulative APS U.S. SAM
($B, '20-50)

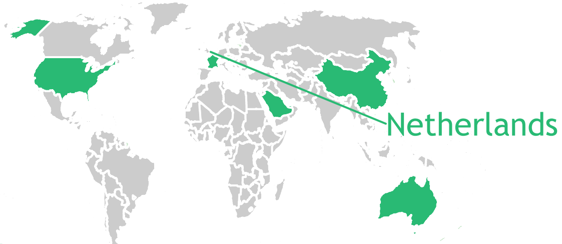
Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	1 - 2	5 - 7	3 - 4
Margin (%)	15 - 20%	15 - 20%	15 - 20%	15 - 20%

Evaluation

Market	Competitive Advantage	Societal Impact

Global players - countries



🟩 Significant[1] number of projects under development

China(~40% of market)
Germany (~20% of market)
Australia(~20% of market)
Netherlands(~10% of market)
US (~10% of market)

Companies

Cummins
ACWA POWER
eDF
e·on
SINOPEC

Competitive advantages

Existing regulatory env.	Relevant companies in this space operate with indirect to no financial support.	L
Providers/supplier concentration	Market is fragmented, with the top 5 players controlling <40% of the market	L
Market ecosystem maturity	Global and inter-regional markets are emerging, dominated by large energy operators operating on an international scale	M
Financing access	Financing is easily accessed through existing markets: energy developers are using internal revenues to finance hydrogen efforts	L
Trained/skilled labor force availability	Highly specialized skills needed to bring together relevant parties and successfully execute project (e.g., secure offtaker agreement, contract suitable RE portfolio)	H

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1. Significant = more than 4 new projects under development, Saudi Arabia included due to 4,000 MW project

Source: IEA Future of Hydrogen; IEA Hydrogen Project Database (2021); Hydrogen Council Insights 2021; Global Data; Project Team; BCG Analysis

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Low-carbon Hydrogen | Financing

High	Medium	Low	N/A

Description of technology value segment

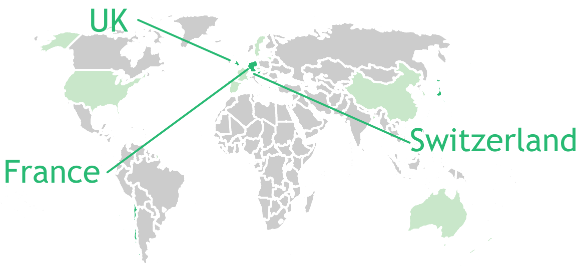
Financing for low-carbon hydrogen involves securing capital for large-scale projects and providing research funding into nascent electrolyser, reformation and transport technologies

$35 - 45B
Cumulative APS U.S. SAM
($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	<1	1 – 2	1 - 2
Margin (%)	<5%	<5%	<5%	<5%

Global players - countries



🟩 Private funding readily available

France (~70% of market)
UK (~15% of market)
Switzerland(~15% of market)

Companies

SIEMENS
John laing
TPG
CREDIT SUISSE
MACQUARIE
ANTIN INFRASTRUCTURE PARTNERS
CA
BNP PARIBAS
SOCIETE GENERALE
BlackRock

▨ Majority government-backed funding

Value proposition

Financing plays an important role in certain areas of low-carbon hydrogen (e.g., OEM, Transport & Storage). Many efforts are being funded internally by large energy providers who are developing projects in house (e.g., Shell). It is important to note however, that government financial incentives (e.g., carbon tax, subsidies, PTC) will be critical to reach cost-competitiveness and encourage global uptake of low-carbon hydrogen

Evaluation

Market	Competitive Advantage	Societal Impact

Competitive advantages

Financing access	Financing for parts of the hydrogen value chain is highly dependent on segment (e.g., govt' funding is needed for R&D, for EPC and O&M, there is private capital from existing energy developers)	M

Source: Center for Strategic International Studies; Reuters; Energy Monitor; Hydrogen Council Investor Group; ANA Group; BCG Analysis

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Low-carbon Hydrogen | EPC

High	Medium	Low	N/A

Description of technology value segment

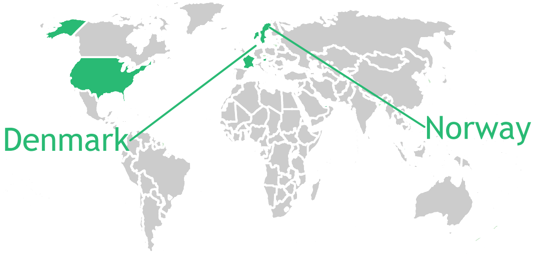
Engineering, procurement & construction (outsourced or inhouse) of Electrolyser stack and systems, Reformer (ATS/SMR), CCUS technology, supply chain mgmt., contractor mgmt., system testing.

$105 - 130B
Cumulative APS U.S. SAM
($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	1 - 2	5 - 7	3 - 4
Margin (%)	5 - 10%	5 - 10%	5 - 10%	5 - 10%

Global players - countries



🟩 Company offering stand-alone EPC services

Denmark (~40% of market)	Norway (~30% of market)
US (~10% of market)	Germany (~40% of market)

Companies

EPC
MCDERMOTT
AkerSolutions
COWI
Linde

Value proposition

Given the low concentration of pure-EPC players and requirement for a certain level of skilled labor, the EPC segment is not to be immediately dismissed. However, this market is estimated to remain quite small, and large energy providers with relevant experience are moving in, making this a segment that may not be worth doing a subsequent deep-dive.

Evaluation

Market	Competitive Advantage	Societal Impact

Competitive advantages

Market ecosystem maturity	Companies offering stand-alone services are largely regional in nature. Larger energy developers provide more inter-regional options.	L
Providers/supplier concentration	Few companies specialize in EPC-only. Larger energy companies are beginning to create EPC divisions in order to address market need (e.g., McDermott, Argan, Inc)	L
Trained/skilled labor force availability	Chemical/industrial asset creation requires highly skilled labor	H

Source: Project Team; McDermott; Aker Solutions; BCG Analysis

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Low-carbon Hydrogen | Energy Inputs

High	Medium	Low	N/A

Description of technology value segment

Energy inputs for green hydrogen include renewable energy (e.g., PV, wind) and natural gas for blue hydrogen

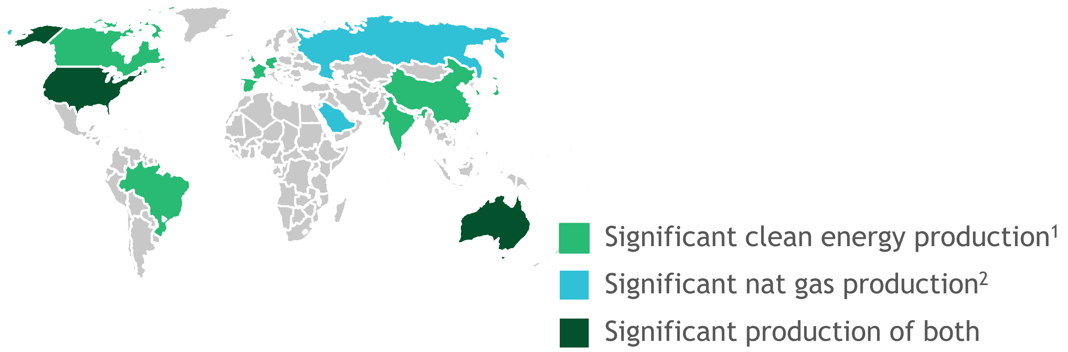
Not applicable

Cumulative APS U.S. SAM ($T, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	*Not applicable*			
Margin (%)	*Not applicable*			

Global players - countries | Companies



Value proposition

Necessary access to low-cost, regional and high-capacity factor RE for green H_2 production, makes Energy Inputs a critical enabler of this value-chain. Given the geographically constrained nature of low-carbon H_2 energy inputs, securing access will support growth throughout the rest of the value-chain. Specific countries, such as the U.S. and Australia, have significant access to both renewables and natural gas production.

Evaluation

Market	Competitive Advantage	Societal Impact

Competitive advantages

Input material availability & concentration	**Green:** RE production makes up ~47% of total system costs[3] with significant cost benefits stemming from localized production. Renewable resources availability is location-dependent and specific countries have developed a clear lead in the space (U.S., China, Australia)	H
	Blue: Natural gas is the largest component of Levelized cost of hydrogen for the blue hydrogen value-chain[3] with significant cost benefits stemming from localized production, which is highly concentrated in a few key players (e.g., U.S., Russia, Australia, etc.)	H
Cost Advantage Potential	**Blue:** Natural gas has an interesting commodity position where LNG is traded globally, however constrained LNG export capacity has created regional pipe gas markets with prices which can be different than global LNG markets	M
	Green: Domestic access to low-cost renewable electricity is an important advantage. Ability to sign PPAs or direct access through on-site generation plant.	M

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1. Defined as having produced >50,000 GWh of zero-carbon electricity (solar PV, wind, hydro, geothermal, and nuclear) in 2021; IEA data 2. Defined as greater than 3,000 BCF of natural gas production in 2020; 3. Green H_2 power costs is derived from a US renewables LCOE based on 50/50 split of onshore wind/utility-scale PV. Ranges for green H_2 reflect variance of electricity across three U.S. regions, CA, TX, and the Midwest. LCOE ranges from $44-52/MWh in 2021 and $28-29/MWh in 2050; 2. iea The Future of Hydrogen

Source: EIA, BCG NAMR Low Carbon H_2 Cost Model; BCG Analysis

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Low-carbon Hydrogen | Operations & Maintenance

High | Medium | Low | N/A

Description of technology value segment

Operations & maintenance for low-carbon hydrogen involves hydrogen generation, management of electrolyser and natural gas facilities and asset monitoring and upkeep

$210 - 260B
Cumulative APS U.S. SAM
($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	2 - 3	10 – 15	15 - 20
Margin (%)	5 - 10%	5 - 10%	5 - 10%	5 - 10%

Global players - countries

🟩 Headquarters of company providing O&M services
France (~40% of market) US (~30% of market)
Germany (~30% of market)

Companies

EDF
Cummins
Air Liquide
Ørsted
bp
e.on
Linde

Value proposition

Despite recent growth in O&M and increased demand, O&M will likely see declining margins due to an increase in market concentration. In addition, there is low potential for durable competitive advantage given the immature market ecosystem, low export potential, commoditized nature of services and low experience level required. O&G are key players in this space who have an established scale-advantage and can leverage existing O&M experience for blue hydrogen operations and maintenance

Evaluation

Market | Competitive Advantage | Societal Impact

Competitive advantages

Trained/skilled labor force availability	Little skilled labor needed, but there is a potential to be first-mover given very limited industry experience with industrial-scale electrolysers	L
Market ecosystem maturity	Existing markets are largely regional, immature and limited in nature	L
Cost advantage potential	Inputs (experience) are global commodities, but there is opportunity for competitive advantage in cost-competitiveness	L

Source: Energy.gov; BCG Analysis

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Low-carbon Hydrogen | Transport & Storage

High	Medium	Low	N/A

Description of technology value segment

Transport & storage for low-carbon H_2 includes conversion (e.g., liquefaction, ammonia/methanol synthesis, hydrogenation), compression, storage (e.g., salt cavern, pressurized/cryogenic tank, and materials), and transport (e.g., gaseous tube trailers, liquid tanker, pipeline and LOHC6)

Value proposition

Improved infrastructure technology for transport and storage is a critical unlock to scaling low-carbon hydrogen. Opportunities for durable competitive advantage exist in potential to create defendable IP in materials storage, which holds significant cost-reduction potential, access to modern pipeline infrastructure, important/export facilities and locality of infrastructure relative to inputs required for producing low-carbon hydrogen (e.g., RE, CO_2 storage sites).

$240 - 300B
Cumulative APS U.S. SAM
($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	2 - 4	10 – 15	15 - 25
Margin (%)	5 - 10%	5 - 10%	5 - 10%	5 - 10%

Evaluation

Market	Competitive Advantage	Societal Impact

Competitive advantages

Existing regulatory env.	New transport & storage projects currently leverage various levels of indirect and direct financial support (e.g., HFTO[5] subsidizes research into transport & storage technology) to scale up and invest in research innovations	M
IP & relevant technical expertise availability	Opportunity to create defensible IP to transport and store hydrogen (Liquid organic hydrogen carriers have the potential to unlock 37% transport cost reductions[3], ammonia cracking has significant potential for cost-effective distribution of hydrogen in long-distance transport[7])	H
Trained/skilled labor force availability	General skilled labor needed, some level of experience for pressurized and pipeline transportation required with parallels to natural gas pipelines	M
Relevant infrastructure potential	>90% of global hydrogen pipelines located in Europe and the US[8], allows for potential to leverage molecule transportation rather than more-expensive electron transport as an energy source	H
	Retrofitting natural gas pipelines is 21-33% of the cost of building a new hydrogen pipeline[1], leveraging US's ~3 million miles of natural gas pipelines can be a significant advantage[4]	H
Financing access	Hydrogen transport and storage research is currently heavily financed through both direct and indirect financial support (e.g., Hydrogen and Fuel Cell Technologies Office conducts research in electrolysers, liquefaction, H_2 carriers, high-pressure tanks, liquid/materials storage[4])	M

Global players - countries

🟩 Natural availability of salt basins for H_2 long-term storage

Denmark (~10% of market)	Netherlands (~10% of market)
Germany (~20% of market)	North America (~60% of market)

Companies

Nouryon

Linde

Air Liquide

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1. European Hydrogen Backbone Study; 3. International Journal of Hydrogen Energy Volume 45, Issue 56: Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers; 4. Energy.gov; 5. Hydrogen and Fuel Cell Technologies office; 7. Ammonia to Green Hydrogen Project_Science & Technology Facilities Council; 8. IEA The Future of Hydrogen
Source: Expert interviews; Sciencedirect – salt caverns; BCG Analysis

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Low-carbon Hydrogen | Offtake

High	Medium	Low	N/A

Description of technology value segment

Use-cases for low-carbon hydrogen are extensive, main applications involve feedstock for industrial production (e.g., refining, ammonia, cement/steel), energy generation (e.g., gas blending, hydrogen combustion turbines), long-haul trucking, chemical production (e.g., ammonia, methanol), fuel-cells for EVs.

Value proposition

Relevant enablers to establishing strong and consistent low-carbon hydrogen demand are captured throughout the rest of the value-chain (e.g., cost reductions, infrastructure, financing). It is important to note that low-carbon hydrogen end-use will heavily depend on regulatory support from governments to reach be cost-competitive (e.g., carbon taxes).

$2.8 - 3.5T

Cumulative APS U.S. SAM

($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	<1	30 - 40	130 – 160	200 - 245
Margin (%)	*Not applicable*			

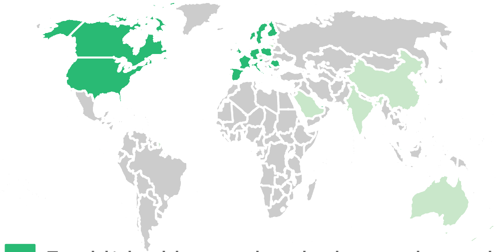
Evaluation

Market	Competitive Advantage	Societal Impact

Competitive advantages

Existing regulatory env.	Efforts to incentivize hydrogen uptake largely require direct financial support (e.g., U.S. Hydrogen Shot to reduce cost of hydrogen 80% to $1/kg by 2030[2], Green Hydrogen Catapult targets $2/kg by 2027; Hydrogen Program Plan has a target of $1/kg for hydrogen industrial and stationary power applications)	H
Relevant infrastructure potential	Existing infrastructure needs upgrades in order to provide access to energy supply. There is opportunity to leverage economies of scale in transportation and unlock +90% cost-savings[1]	M
Cost advantage potential	Hydrogen is a global commodity, but as companies seek to decarbonize, low-carbon hydrogen can become a valued energy input. Unlocking cost advantage can incentivize offtake further	M

Global players - countries



🟩 Established low-carbon hydrogen demand

North America (~30% of market)

Europe (~70% of market)

▨ Active growing interest

Companies

Shell, bp, SIEMENS, BALLARD

1. International Journal of Hydrogen Energy Volume 45, Issue 56; 2. Hydrogen Scaling Up Hydrogen Council Report
Source: BCG Global low-carbon hydrogen Demand Model_v26; BCG Analysis

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Low-carbon Hydrogen | Support Services

High | Medium | Low | N/A

Description of technology value segment

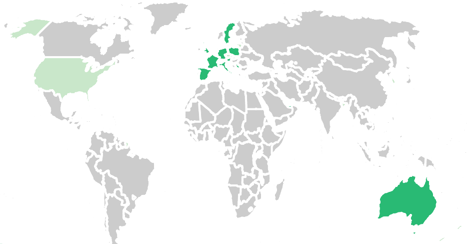
Support services for low-carbon hydrogen includes any auxiliary markets created to support hydrogen deployment and uptake (e.g., hydrogen energy consultant, low-carbon hydrogen certification (e.g., CertifHy)

N/A
Cumulative APS U.S. SAM
($B, '20-50)

Market dynamics

	2020	2030	2040	2050
APS U.S. SAM ($B)	*Not applicable*			
Margin (%)				

Global players - countries



🟩 National certification market
EU (~80% of market)
Australia (~20% of market)

▨ Private, small-scale certification markets

Companies

CertifHy

Australian Government
Department of Industry, Science, Energy and Resources

Value proposition

Support services is a very broad market encompassing a variety of auxiliary products. Given the nascent nature of the low-carbon hydrogen market, offtakers have many unmet needs and there is a medium potential to create durable competitive advantage. Furthermore, the very low concentration of players facilitates entrance into this segment of the value chain.

Evaluation

Market	**Competitive Advantage**	Societal Impact

Competitive advantages

IP & relevant technical expertise availability	Technology possibility is unclear, but possibility for medium potential given nascent state of market and significant unmet needs (e.g., integrating hydrogen into operations)	M
Trained/skilled labor force availability	Potential for highly specialized skill (e.g., consulting services) needed as product offering can involve training of workforce for industrial-scale use due to nascent project nature and limited experience	M
Market ecosystem maturity	Markets are largely regional in nature, and still in developmental stages (e.g., Australia's National Hydrogen Strategy, EU's CertifHy)	L

Source: Certifhy.eu; industry.gov.au; Cummins; BCG Analysis

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E.U., Japan, and South Korea offer greatest export opportunity

European Union

Segments included in SAM:
- OEM
- Project Development
- Transport & Storage
- Offtake

Relevant drivers for inclusion:
- The E.U. is spearheading efforts to define standards and regulations around green hydrogen
- As a customs union, trade potential is the same across the E.U.
- Significant electrolyser capacity additions through 2050 are expected to drive significant need for transportation & storage, OEM, and project development services

Japan

Segments included in SAM:
- OEM
- Project Development
- Transport & Storage
- Offtake

Relevant drivers for inclusion:
- One of the first countries to release a national hydrogen plan (2017) and has publicly committed ~$6.6B to develop domestic H_2 supply chains
- Limited domestic production capacity presents an opportunity for U.S. to enter the market and supply hydrogen molecules, hydrogen derivatives, and infrastructure to support this market
- Market with significant future low-carbon H_2 demand will likely express a need for novel hydrogen carriers to reduce long-distance transport costs

South Korea

Segments included in SAM:
- OEM
- Project Development
- Transport & Storage
- Offtake

Relevant drivers for inclusion:
- With limited domestic capacity and aggressive hydrogen targets, South Korea has committed to importing significant (>20Mt) of hydrogen by 2050
- Market with significant future low-carbon H_2 demand will likely express a need for novel hydrogen carriers to reduce long-distance transport costs

Source: IEA Global Hydrogen Review 2021; CSIS South Korea's Hydrogen Industrial Strategy

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China and Middle East excluded from US SAM due to economic and trade barriers

China

Segments Excluded from TAM:

- OEM
- Project Development
- Transport & Storage
- Offtake

Relevant policy / economic barriers:

- Persistent tensions between China and US restricting foreign energy imports
  - Lingering effect of US-China trade war at the end of the Trump administration is China's diversification of import partners and increasing domestic energy, to limit its reliance on the U.S.
- Western companies report frequent violations of IP rights in JV agreements, limit value-creation potential
- Chinese electrolyser manufacturers are currently dominating electrolyser market on cost-competitiveness

Middle East[1]

Segments Excluded from TAM:

- Offtake

Relevant policy / economic barriers:

- Limited policies in place to incentivize domestic offtake of low-carbon hydrogen
- Likely to have the capacity and RE resources necessary to meet any future regional low-carbon H_2 demand

1. Middle East: Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen

Source: IEA

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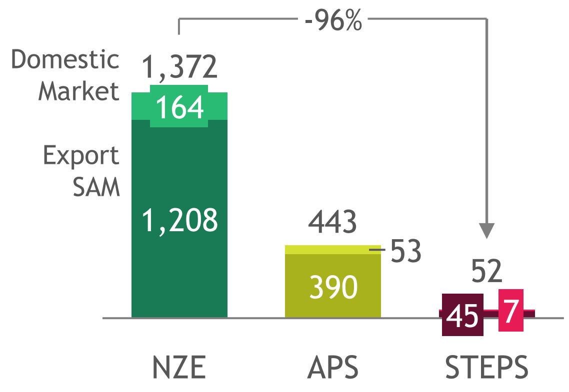
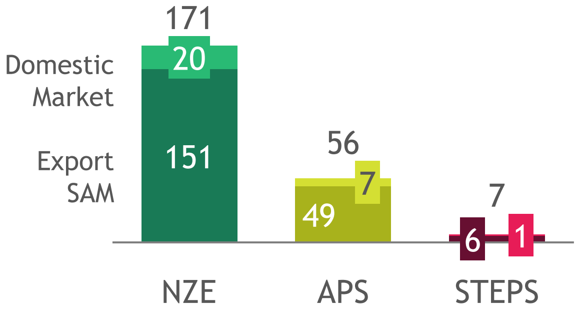
H_2 growth varies significantly across scenarios, possible ~10x growth in APS and ~30x growth in NZE

OEM

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



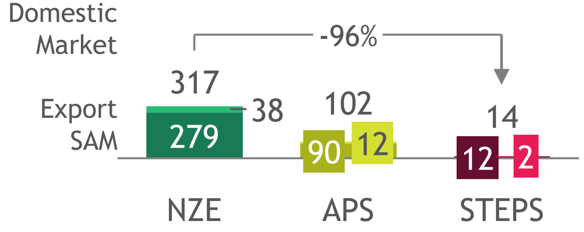
U.S. Serviceable Addressable Market
Margin Pools
(2020 - 2050, $B)



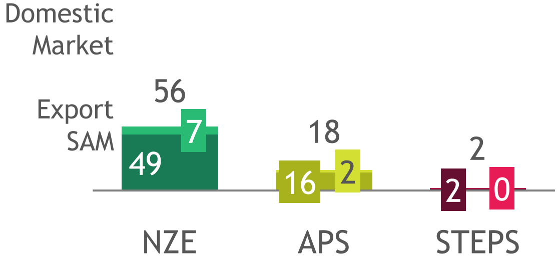
~10 - 15% Est. gross average margin

Project Development

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



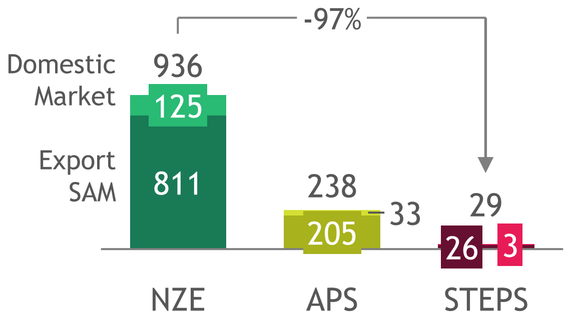
U.S. Serviceable Addressable Market
Margin Pools
(2020 - 2050, $B)



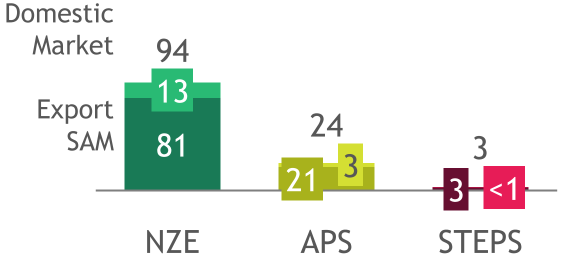
~15 - 20% Est. gross average margin

Transportation & Storage

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



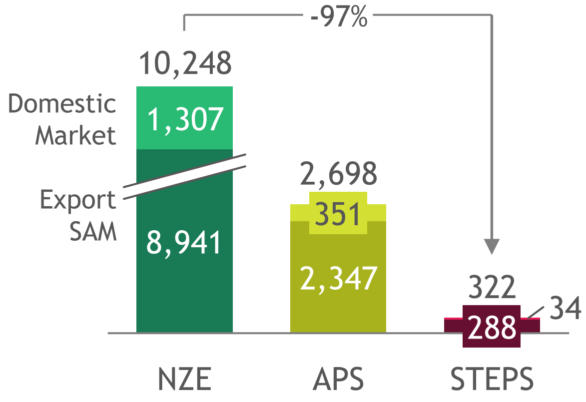
U.S. Serviceable Addressable Market
Margin Pools
(2020 - 2050, $B)



~5- 15% Est. gross average margin

Offtake

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



U.S. Serviceable Addressable Market
Margin Pools
(2020 - 2050, $B)

Not applicable

Source: BCG Analysis

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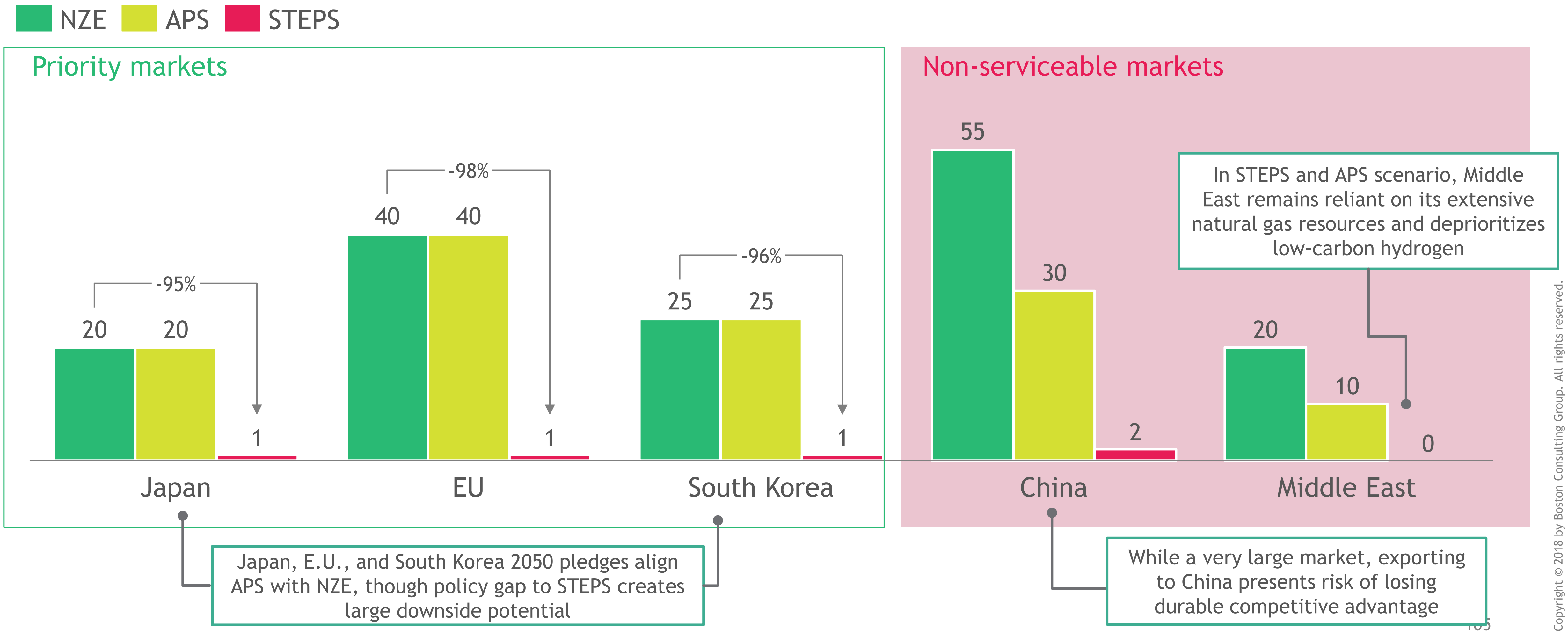
All regions show high scenario-dependency, but priority markets are consistent across APS and NZE scenarios due to net-zero pledges

Low-carbon H_2 production through 2050 by market and scenario (Mt H_2)



In STEPS and APS scenario, Middle East remains reliant on its extensive natural gas resources and deprioritizes low-carbon hydrogen

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

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

Source: BCG Analysis

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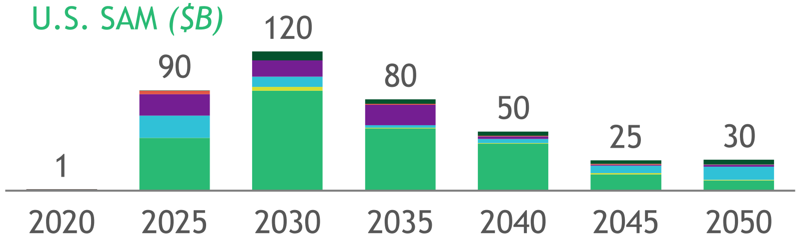
OEM | SAM peaks in ~2030s due to immediate need for ramp up in global capacity to meet decarbonization targets

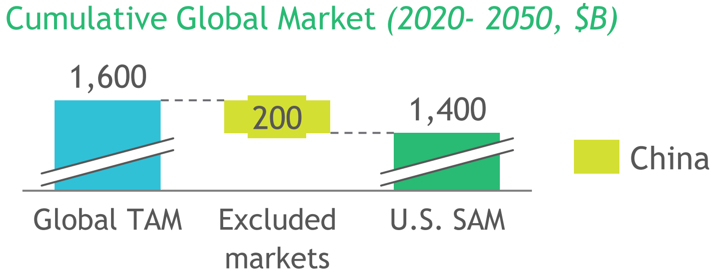
Net Zero Emissions Scenario

■ U.S. ■ Japan ■ EU ■ South Korea ■ Middle East ■ Rest of World

$1.4T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

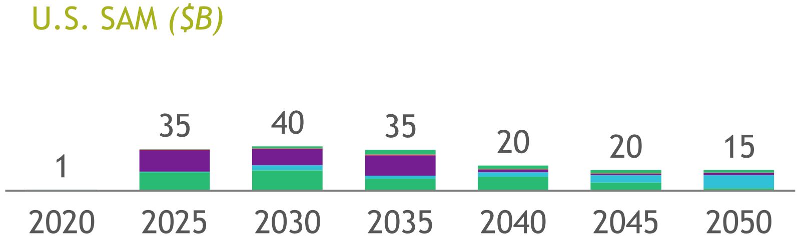


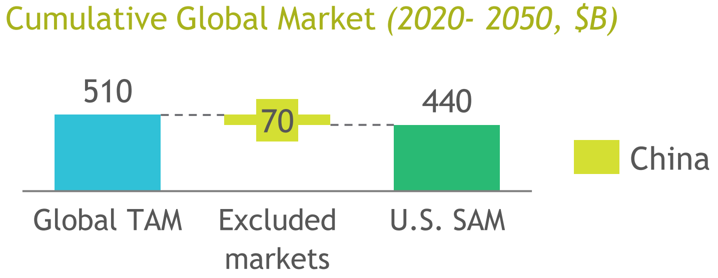


Announced Pledges Scenario

$440B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

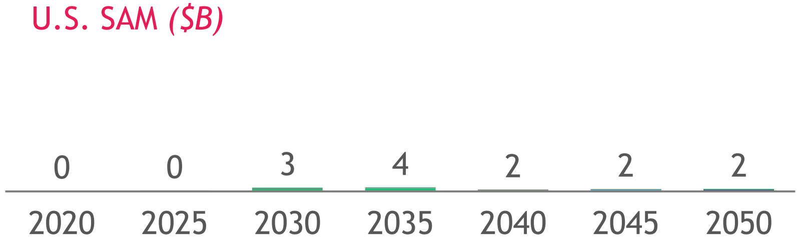


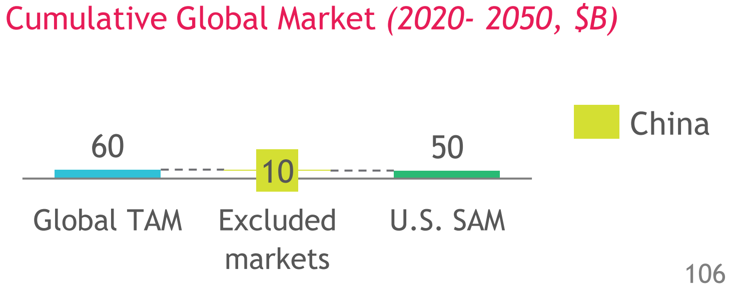


Stated Policies Scenario

$50B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)





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1. Includes both U.S. domestic market and total export SAM
Source: BCG Analysis

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Project Development | SAM value heavily dependent on scenario, with SAM peak in early ~2030s to reflect global ramp up in capacity

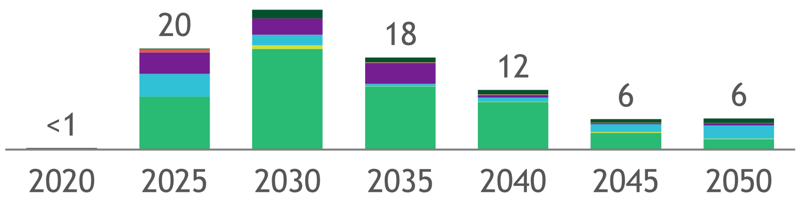
Net Zero Emissions Scenario

🟩 U.S. 🟥 Japan 🟪 EU 🟦 South Korea 🟨 Middle East 🟩 Rest of World

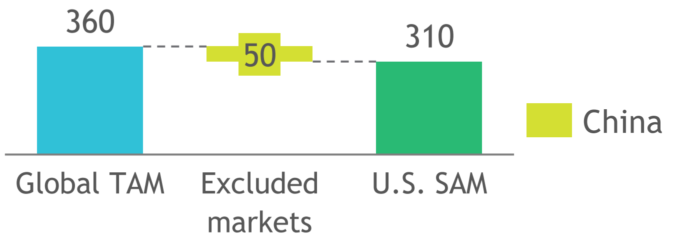
$310B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

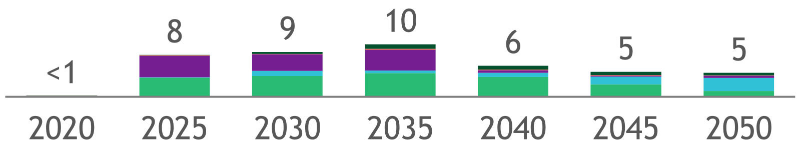


Announced Pledges Scenario

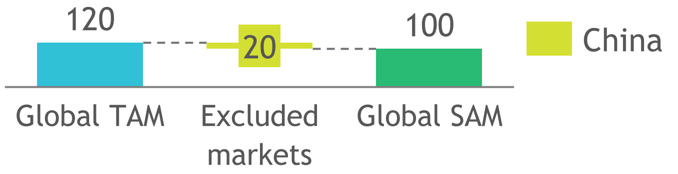
$100B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

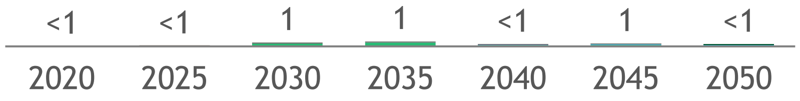


Stated Policies Scenario

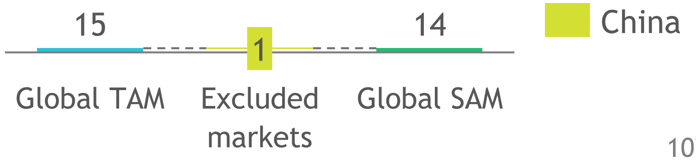
$14B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



1. Includes both U.S. domestic market and total export TAM
Source: BCG Analysis

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Transportation & Storage | SAM growth tracks hydrogen demand forecasts

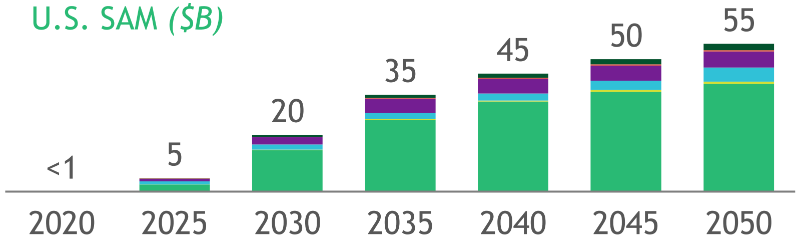
Net Zero Emissions Scenario

■ U.S. 🟥 Japan 🟪 EU 🟦 South Korea 🟨 Middle East 🟩 Rest of World

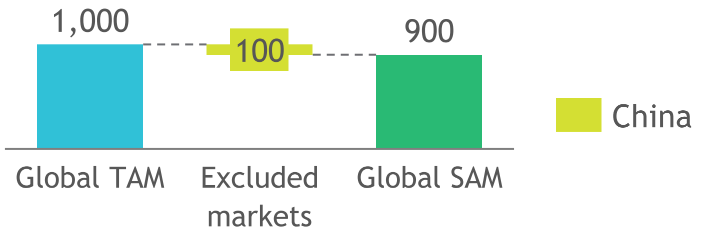
$900B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

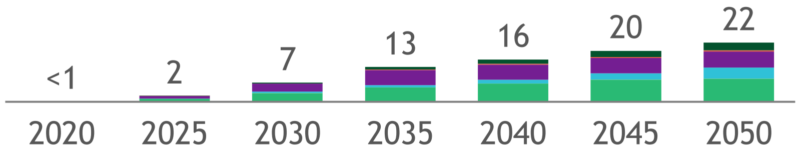


Announced Pledges Scenario

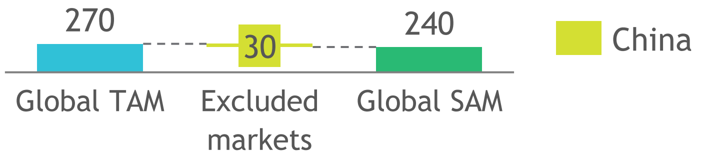
$240B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



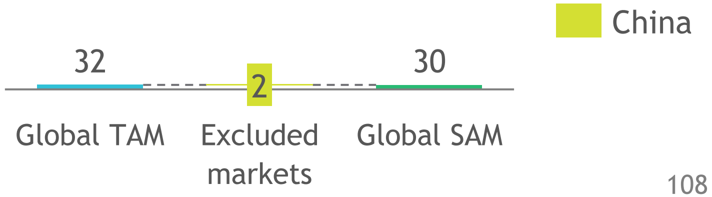
Stated Policies Scenario

$30B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*

Cumulative Global Market *(2020- 2050, $B)*



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[1] Includes both U.S. domestic market and total export TAM
Source: BCG Analysis

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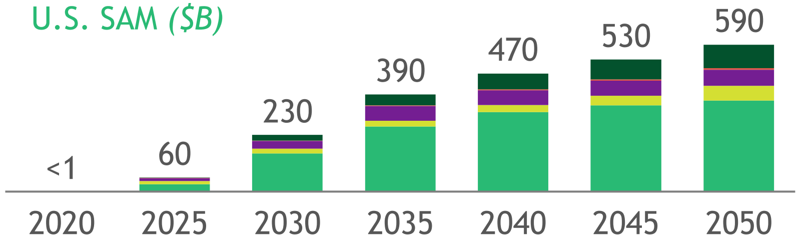
Offtake | Demand for low-carbon H_2 forecasted to grow regardless of scenario

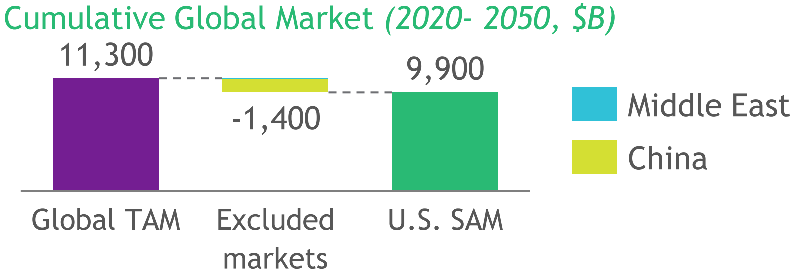
🟩 U.S. 🟥 Japan 🟪 EU 🟨 South Korea 🟩 Rest of World

Net Zero Emissions Scenario

$10T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

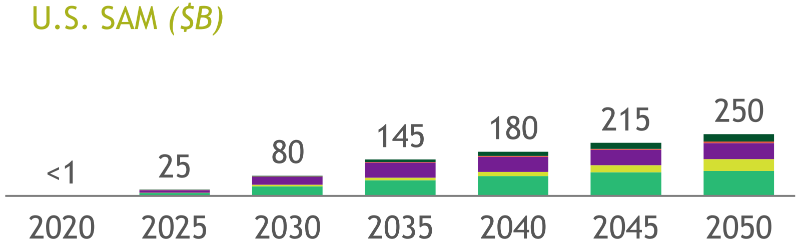

U.S. SAM *($B)*

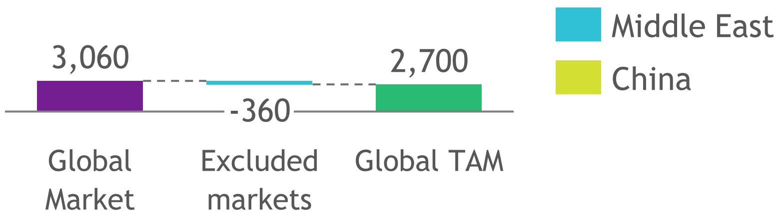

Cumulative Global Market *(2020- 2050, $B)*

Announced Pledges Scenario

$2.7T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)


U.S. SAM *($B)*

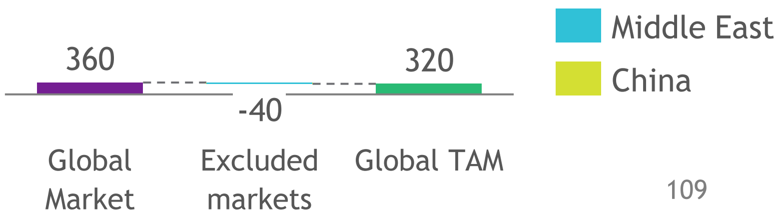

Cumulative Global Market *(2020- 2050, $B)*

Stated Policies Scenario

$320B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)


U.S. SAM *($B)*


Cumulative Global Market *(2020- 2050, $B)*

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1. Includes both U.S. domestic market and total export TAM

BCG Analysis

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Transport & Storage | Europe leading in private sector investments and IP, but U.S. has strong position in demand-side policies and infrastructure

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	• Not applicable in segment
☆ **Intellectual Property & innovation**	Low	• U.S. 4th globally in patent volume for hydrogen transport, distribution and storage (~50) behind Europe (~200), Japan (~150) and China (~150)[1]
Research & technical leadership	Low	• China's literature publication rate for transportation & storage is over 3X the US. However, average quality of those papers is lower, with an average 14 citations vs. 21 for US publications, suggesting leadership of US work is comparatively higher – While publication volume is ~1/3 that of the US, Australia has the highest citation rates of 29, indicating that US research quality is comparable to global leader
Low operational costs	N/A	• Not applicable in segment
☆ **Demand / supply side policy**	High	• U.S.G is supporting infrastructure through DOE HyBlend initiative addressing barriers to blending H_2 in natural gas pipelines (receiving ~$15M funding from '20-'22) and Infrastructure bill allocating $8B for Regional Clean Hydrogen Hubs – Japan has pledged ~$2.8B to developing international supply chains leveraging LOHCs – Germany announced 62 large-scale H_2 projects, including pipeline transport, that are up for funding of up to €8 B under the Important Projects of Common European Interest
Relative domestic market maturity	Low	• Germany has largest private sector investment into hydrogen storage and compressions (~$140 M), with U.S. second (~$80 M), and China third (~$10 M)
☆ **Regulatory environment & existing infrastructure**	High	• 75% of hydrogen salt cavern storage sites operating globally are located in the United States • >90% of global hydrogen pipelines are in Europe and the U.S., with ~1,600 miles of dedicated domestic H_2 pipelines
Overall ranking	🟩	U.S. has a strong existing competitive advantage and should maintain it due to strong demand-side policies and existing infrastructure

1. Data is for 2010-2019

Source: IEA Global Hydrogen Review 2021; DOE; NREL; A hydrogen strategy for a climate-neutral Europe (8/7/2020)

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Project Development | U.S. has strong demand-side policies and high blue H_2 market maturity, but has room to grow in green H_2 project development

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	- Not applicable in segment
Intellectual Property & innovation	N/A	- Not applicable in segment
Research & technical leadership	N/A	- Not applicable in segment
☆ **Low operational costs**	High	- U.S. has significant solar and wind resources, providing access to regional low-cost clean electricity
☆ **Demand / supply side policy**	High	- DOE Hydrogen Shot seeks to reduce the cost of clean hydrogen by 80% to \$1/kg H_2 by 2030, which if achieved would drastically incentivize domestic offtake - EU policy supports low-carbon hydrogen offtake by setting a 50% target for renewable hydrogen consumption in industry by 2030 in its Fit for 55 package
☆ **Relative domestic market maturity**	Low	- EU (\$250 M) global leader in early-stage venture capital deals for hydrogen-relates start-ups, with U.S. second (\$150 M) - North America is significantly behind in green H_2 project development (7 projects in development), with Asia (603), Europe (295), and Oceania (85) leading the way. However, North America is leading in active blue H_2 projects (3.7Mtpa), with Europe in 2nd place (0.4 Mtpa)
Regulatory environment & existing infrastructure	N/A	- Not applicable in segment
Overall Ranking		U.S. has a potential to build a durable competitive advantage in project development due to its strong position in key dimensions for this segment such as access to low-cost RE and favorable demand-side policies, but lower durability of export potential

1. Data is for 2010-2019

Source: IEA Global Hydrogen Review 2021; DOE; A hydrogen strategy for a climate-neutral Europe (8/7/2020); GlobalData October 2021

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OEM | U.S. has strong demand-side policies and market maturity, but falls short in Raw material availability, IP and Skilled workforce

☆ = *Key dimension*

	Areas for Competitive Advantage	Ranking	Summary analysis
☆	**Raw material availability**	Low	• China and South Africa control over 90% of global mining for critical electrolyser materials (e.g., Pt, Co, Ir, Gd, Ce, Zr) • Since 1900, 90% of PGE production has come from South Africa and Russia • U.S. is the 5th largest platinum producer in the world
☆	**Intellectual Property & innovation**	Low	• US 4th globally in OEM patent volume in hydrogen (434) behind China (1,445), Japan (1,249), and South Korea (696) – Despite gap in patent volume, U.S. ranks 3rd in the Global Innovation Index (GII), followed by South Korea (5th), China (12th) and Japan (13th) • The manufacturing complexity of electrolysers creates opportunity for significant research breakthroughs. Novel stack composition can have major impacts on efficiency, lifetime, and cost, making IP the most relevant for driving a competitive advantage • US companies like Cummins, NextEra, Bloom Energy, and Plug Power making global plays in electrolyser research and manufacturing
	Research & technical leadership	Low	• China's literature publication rate for hydrogen research is over 3X the US. However, average quality of those papers is lower, with an average 24 citations vs. 29 for US publications, suggesting leadership of US work is comparatively higher – While publication volume is ~1/3 that of the US, Australia has the highest citation rates of 30, indicating that US research quality is comparable to global leader
	Low operational costs	N/A	• Not applicable in segment
☆	**Demand / supply side policy**	High	• U.S. Infrastructure Bill allocated $1 B for a Clean Hydrogen Electrolysis Program to reduce costs of producing hydrogen from clean electricity – France's "France 2030 Plan" commits $2 B for green hydrogen production, Germany's National Hydrogen Strategy pledged ~$7.6 B[2], while Japan has dedicated ~$0.7 B for domestic renewable H_2 production, indicating wide range of global commitments, but U.S. can be compared to top players
	Relative domestic market maturity	High	• U.S. private sector leads global investments in electrolysers ($179 M), followed by China ($173 M) and Germany ($156 M) • U.S. is dominating in blue hydrogen investments ($563 M) with China ranking 2nd ($69)
	Regulatory environment & existing infrastructure	N/A	• Not applicable in segment
	Overall Ranking		U.S. has a potential to build a durable competitive advantage due to leading position in blue H_2, strong demand-side policies and private sector investments

1. Citation range for top 11 countries with hydrogen academic literature publications is 15.2-30; 2. Subset of funding allocated towards hydrogen production

Source: U.S.GS.gov; Global Innovation Index 2021; Elysee.fr; bmwi.de

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Offtake | EU leads the way with strong policies and regulatory environment, but U.S. has potential due to low costs and domestic market maturity

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	
Intellectual Property & innovation	N/A	
Research & technical leadership	N/A	
Low operational costs	High	• **BH2**[1]: Access to low-cost natural gas feedstock and energy inputs place the U.S. in a strong position to offer competitively-priced blue hydrogen • **GH2**[1]: U.S. has significant solar and wind resources, providing access to regional low-cost clean electricity, which makes up ~45% of the current cost of green hydrogen[2]
☆ **Demand / supply side policy**	Low	• U.S. government has not set export, import, or procurement targets for low-carbon hydrogen • EU can provide a benchmark for strong hydrogen offtake demand-side policies, region's Fit for 55 package calls for 50% renewable hydrogen consumption in industry by 2030
☆ **Relative domestic market maturity**	High	• U.S. is one of the world's largest consumers of hydrogen today, accounting for ~13% of global demand, surpassed only by China (~25%)[4]. Potential to substitute low-carbon hydrogen and grow this domestic market is high
Regulatory environment & existing infrastructure	Low	• U.S. lacks formal standards (e.g., carbon intensity requirements) and regulations (e.g., H2 taxonomy, certificate of origin) for low-carbon hydrogen • EU's Certif-Hy program has established hydrogen certification schemes across Europe • Australia's Smart Energy Council launched a national Zero Carbon Certification Scheme for low-carbon hydrogen and its derivatives
Overall Ranking	🟩	U.S. has a potential to build a durable competitive advantage due to low operational costs and strong domestic hydrogen demand, creating opportunity for both blue and green hydrogen offtake

1. BH2 signifies blue hydrogen (i.e., hydrogen produced from reformation + CCS), GH2 signifies green hydrogen (i.e., hydrogen produced from electrolysis powered by renewables); 2. BCG Low-carbon Hydrogen cost model; 4. IEA Global Hydrogen Review 2021

Source: industry.gov.au; certifhy.eu; consilium.Europa.eu; Global Innovation Index 2021

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Overview of key assumptions

Assumption	Value	Impact on Calculations	Source
2030 %BH2[2] and %GH2[2] global supply for STEPS, APS, and NZE scenarios hold through 2050	%BH, %GH: • STEPS: 23%, 77% • APS: 30%, 70% • NZE: 46%, 54%	The BH2 and GH2 supply assumption determines what proportion of new hydrogen supply projected by the IEA would be low-carbon hydrogen compared to gray hydrogen. This drives production values (Mt H2), which in turn drive all market values and job impact estimates.	IEA World Energy Outlook 2021
2030 total low-carbon H_2 supply = GH2 + BH2, holds through 2050 across scenarios	Total low-carbon H_2 supply: • STEPS: 78% • APS: 63% • NZE: 67%	The assumption that low-carbon hydrogen supply is composed of solely green and blue hydrogen forecasts a potentially smaller market for total low-carbon hydrogen, as production of other forms such as turquoise and pink are not sized.	IEA World Energy Outlook 2021 Expert Input
Total final hydrogen consumption is a proxy for total final hydrogen supply[1]	1:1 conversion factor US, Middle East, Japan, China, EU	Impacts the geographic distribution of CAPEX, potentially shifting target markets for OEM and Project Development.	Expert Input

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1. Unless obvious outlier (e.g., South Korea); 2. BH2 signifies blue hydrogen (i.e., hydrogen produced from reformation + CCS), GH2 signifies green hydrogen (i.e., hydrogen produced from electrolysis powered by renewables)

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Advanced Nuclear SMR

Advanced Nuclear SMRs | Definition of each segment across value chain

Raw materials & inputs	OEM	Project Development	Financing	EPC	Operations/ Maintenance	Transport & Storage	Offtake	Support Services
Mining and refining of raw materials for: Fuels (enriched uranium, thorium, plutonium) Reactor components (coolants such as water / sodium, graphite, steel, etc.) Balance of plant (metals, wiring, concrete, etc.)	**Intermediate and final manufacturing:** Fuel fabrication (e.g., production of rods, pebbles; MOX recycling) Specialized reactor components (I&C, sensors, valves, etc.) Electricity generation components (turbines, etc.) Final SMR factory production (incorporating all components)	OEM typically identifies potential sites and brings projects to customers (e.g., utilities, govt.) OEM will drive permitting and regulatory review processes	OEM arranges financing via govt. support, private financiers, and supply chain partnerships Given nascent status, govts. often provide significant project financing which may be too risky for private investors	OEM typically drives eng. & procurement, often with dedicated partners Construction may be done by a mix of local vendors (e.g., facility construction) and specialized providers (e.g., reactor welding) with regulator oversight	Energy generation, management of reactor operations, and plant maintenance Refueling of modules and fuel waste mgmt Continuous security & site monitoring	New / existing transmission lines (likely to site in areas with transmission access) Fuel waste transport / storage	Power produced is injected into the bulk electric system or local microgrid High-temperature gas-cooled reactors (HTGRs) may provide industrial heat	Predictive analytic tools for plant operations & maintenance Plant monitoring and operations software

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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

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Advanced Nuclear SMRs | Raw materials & inputs

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Raw materials & inputs for SMRs include fuels such as uranium (or plutonium/thorium), coolants (such as fluoride salts, helium, or lead), moderators (such as graphite), and other materials which comprise the "balance of plant" (such as steel, concrete, rubber, wiring, etc.)

$25 - 35
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	<$1B	$1 - 2B	$2 - 3B
Margin (%)	-	30 - 60%	30 - 60%	30 - 60%

GLOBAL PLAYERS - COUNTRIES

🟩 Significant uranium mining

▨ Significant uranium enrichment[2]

COMPANIES

KAZATOMPROM

orano

URANIUM ONE ROSATOM

VALUE PROPOSITION

There is significant potential competitive advantage in the uranium mining and enrichment processes due to concentration of the world's uranium reserves and enrichment capacity, creating opportunity for new entrants. New areas, such as recycled fuels (MOX) and HALEU, may also show potential for new entrants

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	Uranium production is highly concentrated, with 6 countries owning ~85% of global production. While potential exists to recycle spent fuel or repurpose weapons-grade uranium, majority of fuel is from mining activities	H
Existing regulatory env. supportiveness	Relevant companies, particularly in uranium mining and enrichment, are often state-owned / supported[2]	M
Providers/supplier concentration	~85% of Uranium production is owned by ~10 companies, mostly state-owned	M
IP & relevant technical expertise availability	Nuclear enrichment is a highly technical process, though the knowledge is generally widely known across players	L
Pricing advantage potential	Uranium is a global commodity, with associated spot and future markets	L

1. Based on demonstrated margins by pure-play uranium enrichment mining and enrichment companies (e.g., Urenco) 2. Russia is a dominant player in both uranium mining and enrichment
Note: All values reflect the estimated potential market for enriched uranium to fuel SMR and advanced nuclear SMR plants
Source: BCG Analysis; World Nuclear Association

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Advanced Nuclear SMRs | OEM

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Includes the manufacturing and fabrication of fuels, intermediate components, power generation equipment (e.g., turbines), and the final reactor modules prior to on-site installation. Fuels fabrication includes assembly into fuel rods / pebbles, depending on the specific SMR technology

$135 - 165
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$3 - 4B	$7 - 8B	$3 - 4B
Margin (%)	-	10 - 15%	10 - 15%	10 - 15%

GLOBAL PLAYERS - COUNTRIES

🟩 Manufacturing at scale
🟩 Planning/testing pilot projects

COMPANIES

SMR OEMs

NUSCALE
HITACHI
SMR
Westinghouse
中核集团 CNNC
TERRESTRIAL ENERGY
中国国电 CHINA GUODIAN

Fuel Fabricators

AREVA
ТВЭЛ
GNF Global Nuclear Fuel
Westinghouse

Source: BCG Analysis

VALUE PROPOSITION

OEM presents a clear opportunity to build competitive advantage in a high-value area, both for reactor modules as well as associated fuel fabrication. While fuel fabrication is largely established and concentrated, SMR OEMs are still quite nascent, with several U.S. companies among global leaders

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Multiple countries are current directly subsidizing R&D for SMR designs	H
Providers/supplier concentration	Both fuel and SMR production are highly concentrated, with few players	H
IP & relevant technical expertise availability	SMR designs are nascent, with early movers (e.g., NuScale) gaining clear first-mover advantage	H
Trained/skilled labor force availability	Manufacturing of SMRs is likely to require highly skilled and certified labor, similar to large-scale plants	H
Financing access	Financing for both R&D and module production facilities is a key challenge facing OEM players due to a lack of demonstrated demand and proven projects. Govt. financing has been key to overcoming this "valley of death" for new technologies in the U.S. and other countries	H
Pricing advantage potential	Minor potential to build advantage around labor and component cost inputs between countries	L

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Advanced Nuclear SMRs | Project Development

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Project development for SMRs has largely been driven by the OEM, though once producing at scale, this model may change to be more like solar / wind. Primary challenges include site identification, significant permitting and regulatory review processes, origination (typically with utilities), and arranging financing

$90 - 100
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$2 - 3B	$4 - 6B	$2 - 3B
Margin (%)	-	10 – 15%	10 – 15%	10 – 15%

GLOBAL PLAYERS - COUNTRIES

🟩 Domestic companies active internationally
🟩 Domestic companies active domestically

COMPANIES

NUSCALE
Westinghouse
SMR
HITACHI
TERRESTRIAL ENERGY
edf ENERGY
ROSATOM
中核集团 CNNC
中国国电 CHINA GUODIAN

VALUE PROPOSITION

Given the significant barriers posed by regulatory review/permitting and financing, early govt. intervention can enable a more robust domestic development ecosystem. Emerging trends point to potential for development to extend overseas, making a first-mover advantage valuable (e.g., NuScale)

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Govt. support, both direct project cost-sharing and expedited permitting / regulatory review programs, can provide much-needed support	H
Providers/supplier concentration	Given the small number of regional players today first movers in project development can gain a large advantage	H
Trained/skilled labor force availability	Highly technical aspects of development (e.g., site risk assessments, permitting) require skilled labor to perform	H
Market ecosystem maturity	While current projects are typically developed by domestic players, early leaders (e.g., NuScale) are beginning to build a global market via international development opportunities	L

Source: BCG Analysis

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Advanced Nuclear SMRs | Financing

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Financing is a key challenge for the nuclear industry, including SMRs. Given the high upfront fixed costs, long development timeline, and significant construction risk given the highly complex and technical asset, financing such projects can be costly, particular for new SMR technologies. Govt. financing from the U.S. Ex-Im Bank[1] is used for nuclear exports today

$65 - 80
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$1 - 2B	$3 - 4B	$1 - 2B
Margin (%)	-	8 - 12%	8 - 12%	8 - 12%

GLOBAL PLAYERS - COUNTRIES

- 🟩 Governments provide SMR project financing support
- 🟩 Governments have provided R&D financing support

COMPANIES

Not applicable

VALUE PROPOSITION

Given the capital intensity of SMRs, financing is a key challenge which govt. support can mitigate. Subsidized loans for projects can help de-risk the development of SMRs, helping to nurture a robust domestic market. Export banks can create competitive advantage by providing low-cost debt for projects developed abroad

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Financing access	SMR project financing for pilot projects often includes funds from govt. entities, such as the DoE, through cost-sharing programs. Remaining financing comes from a mix of the OEM, supply chain partners, and the project customer (e.g., utilities). Other countries, notably China, provide support for state-owned companies which are also dedicating significant resources to SMR development. Other projects, such as the Ontario Power Generation project with GEH, will be largely customer-financed similar to conventional nuclear plants. In this case, the utility customer uses balance sheet financing with some degree of guaranteed cost recovery from rate payers. Govt. subsidized loans are used to help assuage regulator concerns and provide a potential benefit to ratepayers	H

1. U.S. Export-Import Bank 2. Margins represent ranges for typical U.S. utility cost of capital who would typically finance conventional nuclear builds
Source: BCG Analysis

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Advanced Nuclear SMRs | EPC

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

SMR EPC involves final on-site plant engineering, procurement, and construction of factory-produced reactor modules, power plant generation equipment, and site facilities. Final on-site construction will typically require regulator oversight and inspection. OEMs typically drive eng. & proc., while local construction vendors are often used

$160 - 190
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$1 - 2B	$3 - 4B	$1 - 2B
Margin (%)[1]	-	5 - 8%	5 - 8%	5 - 8%

GLOBAL PLAYERS - COUNTRIES | COMPANIES

Not applicable

OEMs typically partner with local/regional players as needed

VALUE PROPOSITION

OEMs will typically own the highest-value engineering and procurement portions of EPC, while the construction will often be done by qualified local/regional vendors. As such, there is particular value in focusing on the OEM-owned portions of EPC for potential export

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Providers/supplier concentration	The highly-concentrated OEMs are typically very involved in Eng. & procurement, while actual construction is contracted out to qualified local vendors	H
IP & relevant technical expertise availability	Final site eng. design will typically be done by the OEM and would require significant technical knowledge	H
Trained/skilled labor force availability	Final plant assembly may require some certified / specific types of labor, however large portions (e.g., cement) are fairly standardized and easy to access	M
Pricing advantage potential	Given high degree of labor, local variations in labor costs can provide some degree of competitive advantage for SMR installation and site preparation. Experienced EPCs may reduce costs by avoiding delays / budget overruns	M

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[1] Margins can range much higher for certain niche activities, however overall are expected to be low

Source: BCG Analysis

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Advanced Nuclear SMRs | Operations & Maintenance

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Similar to large reactors, SMRs will likely be operated and maintained by the owning entity (e.g., utilities). This typically entails 24/7 plant monitoring, proactive maintenance, and periodic module refueling. Reactor maintenance is typically done during plant refueling outages, while the surrounding safety and generation components are constantly maintained

$380 - 465
Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	-	$3 – 5B	$20 – 25B	$30 – 35B
Margin (%)	-	5 - 15%	5 - 15%	5 - 15%

GLOBAL PLAYERS - COUNTRIES

🟩 >10 GW total operating nuclear capacity (2020)
🟩 5- 10 GW total operating nuclear capacity (2020)

COMPANIES

Exelon.

eDF

ATOM ENERGO PROM

TEPCO
Tokyo Electric Power Company Holdings

VALUE PROPOSITION

While important, given the market size and the general availability of the skilled labor needed O&M is unlikely to be an area for long-term competitive advantage in the SMR space. Each plant is likely to be operated and maintained locally, reducing the long-term potential and attractiveness of the space

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Trained/skilled labor force availability	O&M for nuclear plants will require a broad range of skilled labor inputs, such as engineers, electricians, welders, etc. In the U.S., some of these skills require specific regulatory certification to ensure that maintenance is of sufficient quality to maintain safety	M

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1. Margins can range much higher for certain niche activities, such as certified nuclear welders, however overall are expected to be low
Source: BCG Analysis

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Advanced Nuclear SMRs | Transport & Storage

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Power produced by SMRs will typically be transported using bulk electric system high-voltage transmission lines. While major upgrades to the transmission networks are needed, particularly to integrate renewables, it is difficult to gauge the impact from SMRs. In some cases, SMRs may form the backbone for local micro-grids not connected to the bulk electrical system

N/A

Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	*Not applicable*			
Margin (%)				

GLOBAL PLAYERS - COUNTRIES COMPANIES

Not applicable

Transmission will be provided by the local utility and/or regional system operator (e.g., ISO/RTO)

VALUE PROPOSITION

Given the large amount of overlap for transmission infrastructure with other industries, there is little direct opportunity related to transport and storage for SMRs

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	While permitting is a key challenge for transmission system expansion, regulatory efforts to ease transmission development challenges do not provide a material opportunity to build SMR competitive advantage	N/A
Relevant infrastructure potential	Given high-voltage electric transmission infrastructure is in place in all major world economies, there is little opportunity to create competitive advantage in this space	N/A

Source: BCG Analysis

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Advanced Nuclear SMRs | Offtake

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

SMR offtake will typically be electricity production or industrial heat. Zero-carbon electricity can be injected into the grid or can provide power for specific microgrids or assets, such as green H_2 electrolyzers. Industrial heat requires High-Temperature Gas-Cooled (HTGR) reactor SMRs, which create far more heat than LWR SMRs, and can decarbonize industrial processes

N/A

Cumulative APS US SAM ($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	*Not applicable*			
Margin (%)				

GLOBAL PLAYERS - COUNTRIES | COMPANIES

Not applicable

Highly local nature of electricity offtake means that all SMRs will require access to transmission infrastructure

VALUE PROPOSITION

Due to the regional or local nature of SMR offtake, there is little opportunity to build competitive advantage in the space. Electricity markets are highly regional, highly regulated, and well-established, while industrial heat offtake is often project-specific

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Market ecosystem maturity	While electricity markets are well-established, they are typically quite regional in nature, making it quite difficult to establish competitive advantage in offtake (such as in the U.S.). Similarly, industrial heat offtake or microgrids will be highly localized, often at the project-specific level, inhibiting the establishment of a broader competitive advantage	N/A

Source: BCG Analysis

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Advanced Nuclear SMRs | Support Services

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

While SMR technology is too nascent to have proven support services, the large reactor space offers some insights. Support services would likely be software-based tools for plant O&M, such as predictive analytics to inform maintenance or automated operations software. Country-specific regulations may hinder the growth of these areas, however, to ensure plant safety

VALUE PROPOSITION

Support services are unlikely to present a significant opportunity in the SMR space. Due to stringent safety requirements for nuclear plant operations uptake of similar services has been low for large-scale reactors, and significant variability across countries inhibits potential for broad advantage abroad

N/A

Cumulative APS
US SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
US SAM ($B, APS)	*Not applicable*			
Margin (%)				

EVALUATION

Market	Competitive Advantage	Societal Impact

GLOBAL PLAYERS - COUNTRIES COMPANIES

Not applicable

Support services opportunities will vary by country based on local nuclear regulations and may require changes to current requirements

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Disparate nuclear regulations across countries will likely inhibit broad competitive advantage across countries, while strict domestic regulations present a high barrier to entry. For example, in the U.S. strict regulations dictate how plants are operated and maintained, while in France passive safety systems are not permitted. Such differences would result in different types of support services in different countries, making it difficult to provide across borders	N/A
IP & relevant technical expertise availability	Several similar tools are already in place for other types of generation assets (e.g., CCGTs, etc.), however regulations have prevented widespread uptake	N/A

Source: BCG Analysis

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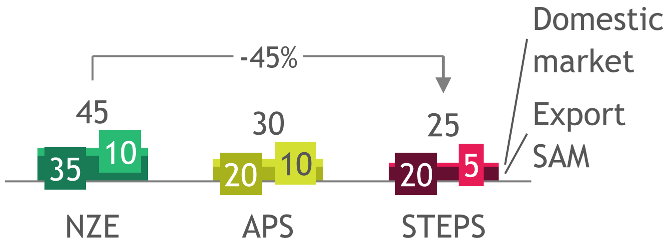
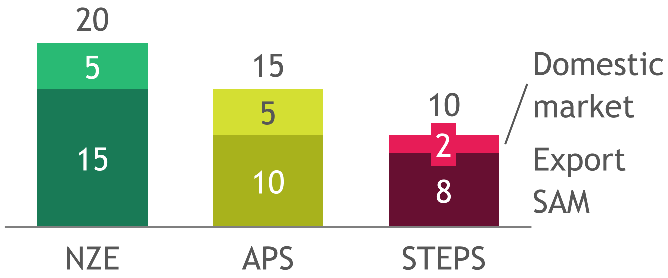
OEM offers strong U.S. market opportunity across scenarios, though market potential falls ~20 - 40% from the Net Zero Emissions scenario

Raw materials

U.S. Serviceable Addressable Market (SAM)
(2020 - 2050, $B)



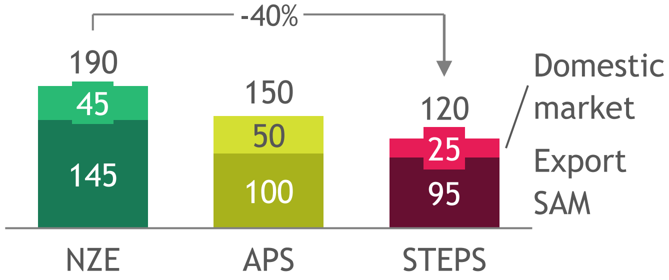
U.S. SAM Margin Pools
(2020 - 2050, $B)



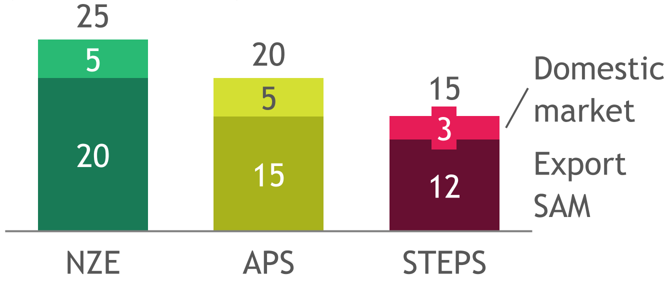
~30 - 60% Est. gross average margin

OEM

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



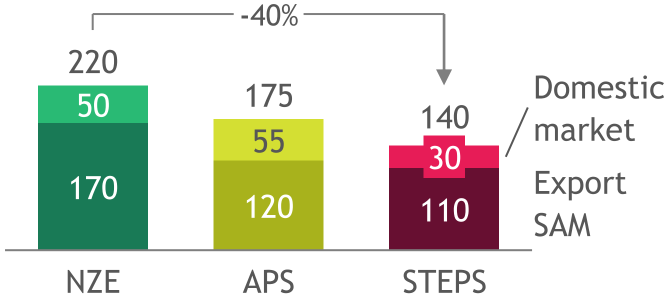
U.S. SAM Margin Pools
(2020 - 2050, $B)



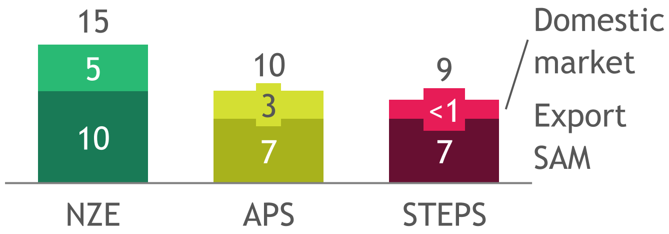
~10 - 15% Est. gross average margin

EPC

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



U.S. SAM Margin Pools
(2020 - 2050, $B)



~5 - 8% Est. gross average margin

Note: All numbers rounded
Source: BCG analysis

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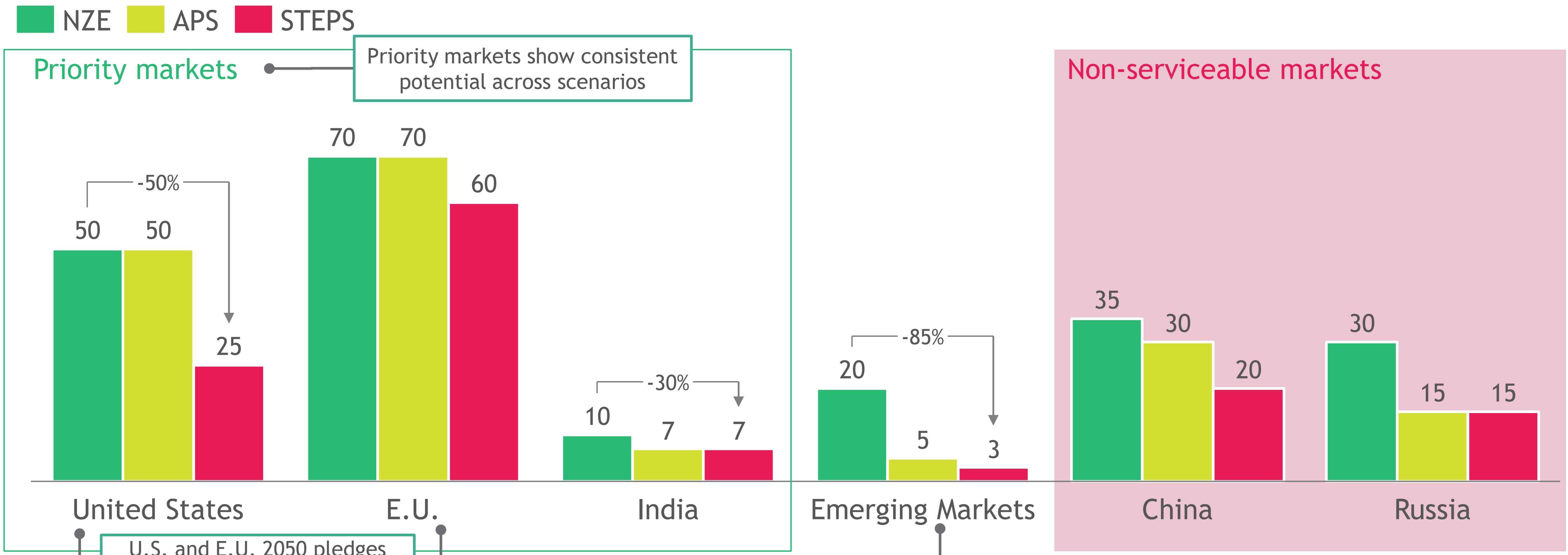
The U.S., E.U., and Indian markets present greatest potential for SMR deployment across scenarios

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

Source: IEA World Energy Outlook 2021; BCG analysis

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Raw materials | NZE scenario has ~2x expected growth of APS and STEPS

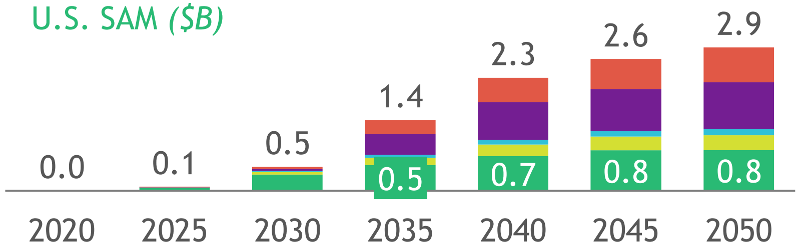
US and Indian markets each account for 10-20% of SAM, while E.U. accounts for an additional ~20-40%

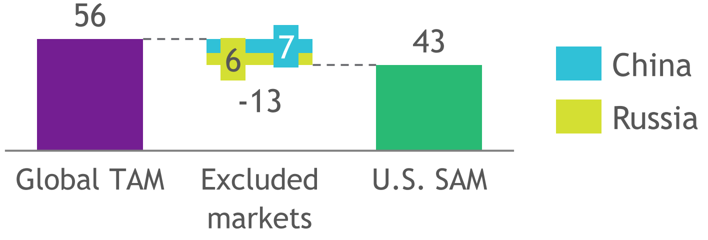
🟥 U.S. 🟪 E.U. 🟦 India 🟨 Emerging Markets 🟩 Rest of World

Net Zero Emissions Scenario

$45B

Cumulative U.S. Serviceable Addressable Market¹ *(2020 - 2050)*

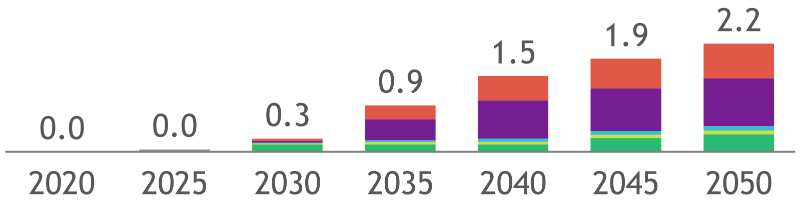

U.S. SAM *($B)*

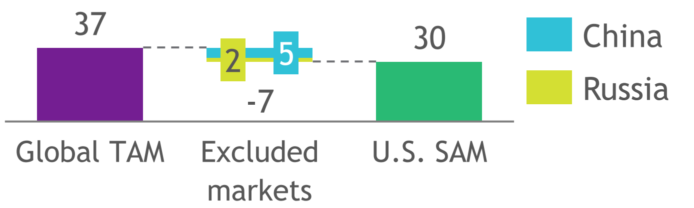

Cumulative Global Market *(2020- 2050, $B)*

Announced Pledges Scenario

$30B

Cumulative U.S. Serviceable Addressable Market¹ *(2020 - 2050)*

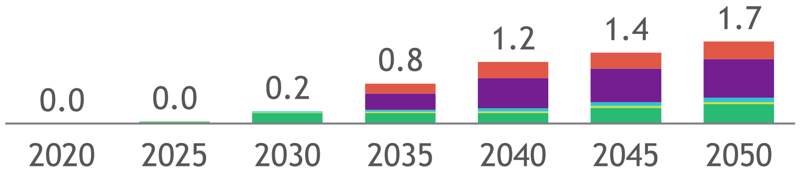

U.S. SAM *($B)*

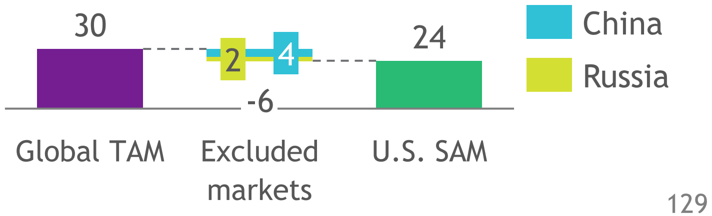

Cumulative Global Market *(2020- 2050, $B)*

Stated Policies Scenario

$25B

Cumulative U.S. Serviceable Addressable Market¹ *(2020 - 2050)*


U.S. SAM *($B)*


Cumulative Global Market *(2020- 2050, $B)*

1. Includes both U.S. domestic market and total export TAM

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OEM | Market value is expected to peak 2030 – 2040 across scenarios

U.S. & E.U. retains value outside NZE as aging nuclear is replaced, while emerging markets lose most value

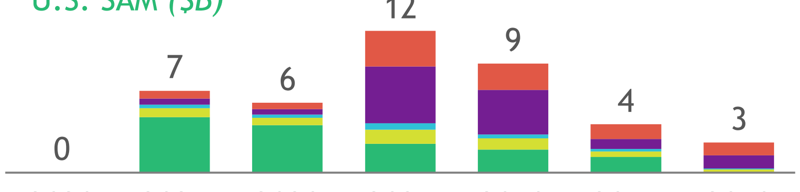
🟥 U.S. 🟪 E.U. 🟦 India 🟨 Emerging Markets 🟩 Rest of World

Net Zero Emissions Scenario

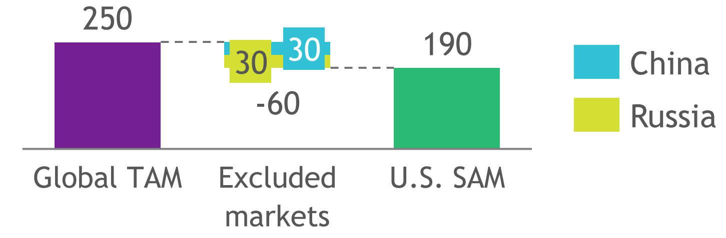
$190B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



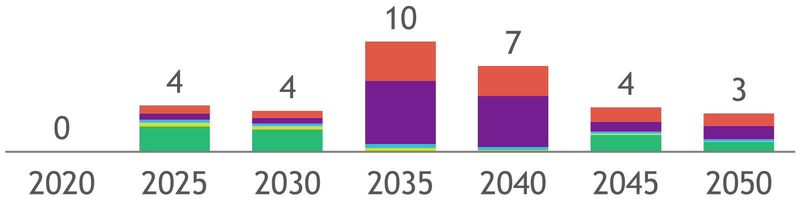
Emerging markets lose most value under outside of NZE, while U.S. & E.U. retain value

Announced Pledges Scenario

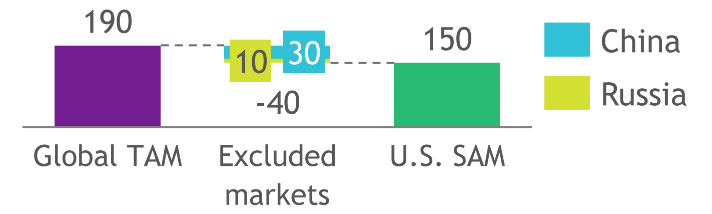
$150B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

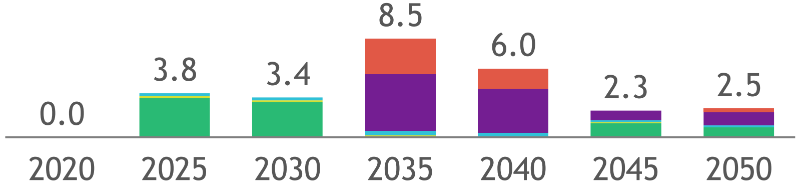


Stated Policies Scenario

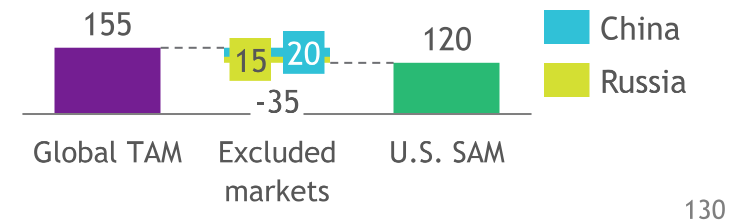
$120B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



1. Includes both U.S. domestic market and total export TAM

Note: All numbers rounded

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EPC | Similar to OEM, market value peaks 2030 – 2040 across scenarios

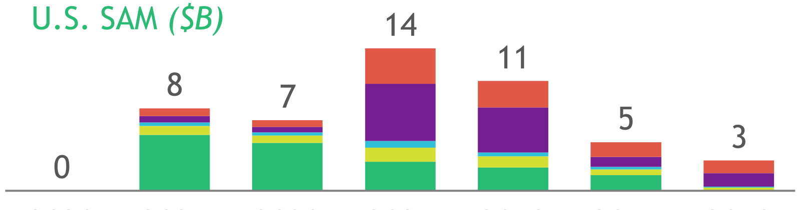
E.U. drives significant growth, particularly in the APS and STEPS scenarios as other markets decline

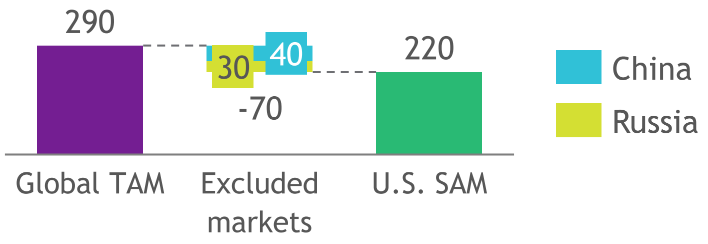
🟥 U.S. 🟪 E.U. 🟦 India 🟨 Emerging Markets 🟩 Rest of World

Net Zero Emissions Scenario

$220B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*


U.S. SAM *($B)*

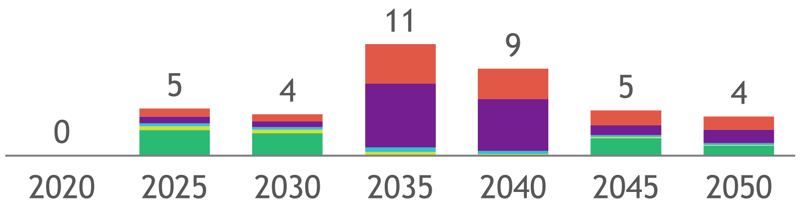

Cumulative Global Market *(2020- 2050, $B)*

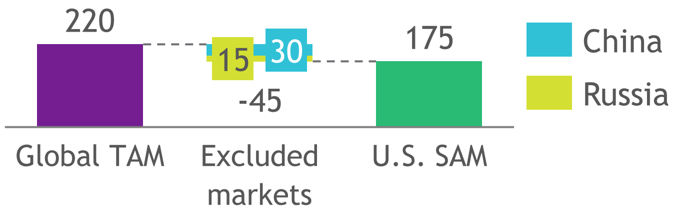
Emerging markets lose most value under outside of NZE, while U.S. & E.U. retain value

Announced Pledges Scenario

$175B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

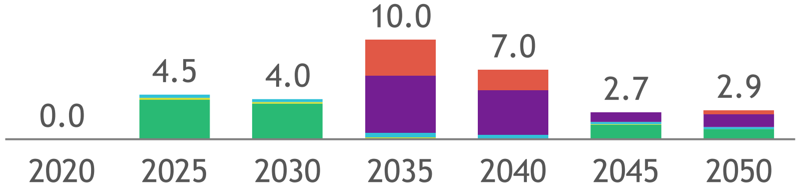

U.S. SAM *($B)*

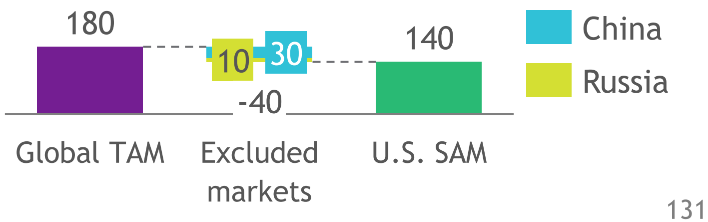

Cumulative Global Market *(2020- 2050, $B)*

Stated Policies Scenario

$140B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*


U.S. SAM *($B)*


Cumulative Global Market *(2020- 2050, $B)*

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1. Includes both U.S. domestic market and total export TAM

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Raw Materials | The U.S. does not hold a clear advantage in the strategic uranium enrichment space, though DOE programs are seeking to close the gap

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
☆ **Raw material availability**	Low	- The U.S. has produced <5% of the world's raw uranium since 2011, with the value decreasing steadily since 2017 to nearly nothing in 2020. Further, the U.S. possesses <10% of the world's uranium enrichment capacity, while Russia and Europe hold ~40% and 30% of global enrichment capacity, respectively
Intellectual Property & innovation	Low	- U.S. ranks 5th globally in patent volume related to nuclear fuel production, behind China, Japan, Russia, and France. China maintains a significant lead, with nearly ~14x the patents as the U.S. and ~7x the patents of Japan and Russia - Despite gap in patent volume, the U.S. ranks 3rd in the Global Innovation Index (GII), followed by France (11th), China (12th), Japan (13th), and Russia (45th) - Majority of IP is driven by Chinese research institutions and vertically integrated uranium players (e.g., Orano, Rosatom)
Research & technical leadership	High	- Although China maintains a ~1.5x lead over the U.S. in terms of research paper volumes, U.S. research is largely led by the DOE, the most prolific single research institute in the space globally. - Further, the U.S. maintains a slight edge in research quality compared to Chinese research based on citations
Low operational costs	N/A	- Not applicable in segment
Demand / supply side policy	High	- The U.S. DOE was authorized under the Energy Act of 2020 to launch the HALEU Availability Program to spur private investment in nuclear fuel supply infrastructure to enable access to commercially available HALEU for advanced reactors
☆ **Relative domestic market maturity**	Low	- Canadian, Russian, and French players comprised the majority of investment into the fuel supply chain - U.S. players made few investments, though the DOE ARDP recently announced a cost sharing program with X-energy to produce HALEU-based TRISO fuel for advanced reactors
☆ **Regulatory environment & existing infrastructure**	High	- While the U.S. has limited uranium enrichment capacity for civilian nuclear reactors, the DOE's National Nuclear Security Administration (NNSA) enriches uranium to a range of levels, primarily to support defense missions (e.g., Naval Reactors program). This technical talent and know-how could likely be leveraged to support a domestic civilian industry as well
Overall ranking		U.S. has **low competitive advantage potential** today, largely due to a lack of domestic civilian enrichment capacity and a lack of a mature market to incentivize private investment, but has strong incentive to build

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OEM | The U.S. holds an early lead in the SMR OEM space across relevant dimensions

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	• Not applicable in segment
☆ **Intellectual Property & innovation**	High	• The U.S. maintains a slight, early lead in SMR-related patents, closely followed by South Korea (2nd) and China (3rd) • Reinforcing this early lead, the U.S. ranks 3rd in the Global Innovation Index (GII), followed by Korea (5th) and China (12th) • Large nuclear players, such as Westinghouse or China's CNNC, tend to drive patents, potentially implying a relatively direct path to SMR IP commercialization
☆ **Research & technical leadership**	High	• The U.S. maintains a slight lead in the publication of SMR-related papers (~70), followed closely by China (~45), followed by the U.K. and South Korea (~25 each). Notably, both Iran and Canada are also active on the topic (~18 each) • The U.S. also leads in terms of research quality, measured in terms of average citations
Low operational costs	Low	• U.S. labor is generally costlier than other markets (e.g., China), both for R&D / engineering roles as well as manufacturing labor
Demand / supply side policy	High	• The U.S. DOE Advanced Reactor Demonstration Program (ARDP) funds multiple advanced reactor technologies at multiple stages of the design lifecycle, from initial designs to demonstration plants (such as TerraPower and X-Energy) • State-level clean energy targets also encourage the buildout of new nuclear capacity as aging plants are decommissioned
Relative domestic market maturity	High	• U.S. companies lead private investment in the SMR space, totaling ~3 - 4x the investment made by the U.K. and Canada, which are 2nd and 3rd in private investment, respectively
☆ **Regulatory environment & existing infrastructure**	High	• The U.S. has the largest operating nuclear fleet in the world, enabling a relatively robust domestic industry with relevant technical and commercial expertise • Likewise, the U.S. DOE and Nuclear Regulatory Comission (NRC) are generally viewed as the gold standard in nuclear research and licensing globally, giving U.S.-based companies a boost in terms of credibility and reputation aborad • Coal plant retirements present the U.S. with a unique opportunity to rapidly deploy SMRs by leveraging pre-existing site infrastructure (e.g., water access, transmission interconnections, etc.)
Overall ranking	🟩	U.S. found to have **competitive advantage potential** due to early leadership in IP, research, and commercialization of domestic technologies

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EPC | The U.S. lacks competitive advantage in the EPC space

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	• Construction materials (e.g., cement) are widely available
Intellectual Property & innovation	N/A	• EPC competitive advantage is not driven by patents
Research & technical leadership	N/A	• EPC competitive advantage is not driven by research paper publication
Low operational costs	Low	• U.S. labor costs are typically higher than other countries
Demand / supply side policy	N/A	• EPC competitive advantage is not driven by policies
☆ **Relative domestic market maturity**	Low	• The U.S. has little investment in the nuclear EPC space, which is primarily lead by countries building new capacity such as China (which makes up ~40% of planned capacity), India (~12%), and Korea (~10%) • Further, recent U.S. new nuclear builds have had significant timeline delays and budget overruns while projects in other markets (e.g., China, Korea) have generally been completed on time and on budget, which does not reflect positively on U.S. EPC players
Regulatory environment & existing infrastructure	Low	• A lack of recent nuclear new build activity in the U.S. has limited the ecosystem for nuclear EPC players, as shown by difficulties in recent new builds (e.g., Vogtle)
Overall ranking		U.S. found to have low competitive advantage in EPC due to highly mature market relative to others but low activity in the IP / research space

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Overview of key assumptions

Assumption	Value	Impact on Calculations	Source
Projections of nuclear capacity additions	*Varies by year, market, and scenario*	Forecasted nuclear capacity additions form the base of the model, impacting the total SMR capacity deployed, segment-specific market values, and in turn job growth potential. Current IEA inputs are viewed as conservative, as the IEA projections were based on historical nuclear costs and do not account for the potential cost decreases targeted by SMR vendors	IEA 2021 World Energy Outlook
Est. SMR penetration projections	*Varies by market*	Once the total nuclear capacity additions are estimated per market, an estimated SMR penetration is applied to calculate the new nuclear capacity which would be from SMRs as opposed to conventional large-scale nuclear. The total new SMR capacity is then used to calculate market values per value chain segment	Nuclear Energy Agency;[1] Expert input
SMR installed costs	First of a Kind (FOAK) = ~$4,770/kW Nth of a Kind (NOAK) = ~$2,550/kW	The SMR installed costs are applied to the estimated SMR capacity additions to calculate total spend to install new SMR capacity built over time. This largely applies to the OEM, project development, financing, and EPC segments which are directly tied to the construction of new SMR capacity. All values reflect the average cost calculated using multiple SMR designs	Energy Information Reform Project;[2] BCG analysis[3]
Year NOAK costs are achieved	NZE = 2040 APS = 2045 STEPS = 2050	The rate of cost decline is determined by calculating the CAGR needed to achieve the NOAK cost by the target year. This determines the estimated installed cost in each year, which is applied to the SMR capacity deployed in that year to calculate the total installed costs across OEM, project development, financing, and EPC segments	Expert input

---

1. Nuclear Energy Agency (NEA) - Small Modular Reactors: Nuclear Energy Market Potential for Near-term Deployment 2. Energy Innovation Reform Project – What Will Advanced Nuclear Plants Cost? 3. Based on BCG work with an SMR player, assuming a learning rate of ~10% based on demonstrated learning rates for similar technologies per installed cost driver, for total reduction of ~40-50% in costs

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DAC

DAC | Definition of each segment across value chain

Raw materials & inputs	OEM	Project Development	Financing	EPC	Operations/ Maintenance	Transport & Storage	Offtake	Support Services
Natural resources used for: **Solid sorbent** (alkanolamines, chemically-produced) **Liquid solvent** (alkali, alkaline earth metal hydroxides - often potassium or sodium hydroxide)	Manufacturing & designing technology Solid sorbent & liquid solvent: • Amine-based sorbent Plant components: • Air contactor fan • Compressor • Steam/ vacuum chamber • Pellet reactor • Slaker • Calciner • Heat regenerator	Project origination & coordination Site selection: • Humidity • Temp. • Large, uninhabited space Permissions & contracting Secure financing Energy inputs (currently, mix of RE and natural gas)	Full financing capital stack for large-scale projects Significant grant funding from DoE Private equity, venture capital investment, grants, and voluntary offsets to encourage innovation Government grants, favorable loans for R&D	Engineering, procurement & construction (outsourced or inhouse) • **Solid** - detailed eng. design fit for purpose • **Liquid** - detailed eng. design that combines existing components • Supply chain mgmt • Contractor mgmt. • System testing	Operations & maintenance • Sorbent/ solvent regeneration • Baseline operations • Asset monitoring • Maintenance & repairs	Logistics of compressed CO2 delivery Long-term storage: • Saline aquifers • Depleted oil wells • Injection machinery Local transport logistics: • Pipeline • Pumps	End usage for either carbon offsets or CO2 gas (e.g., EOR, synfuels) • Final offtake contracting • Sales channels / markets	Differentiated offerings to ensure offset quality & expand DAC plant creation E.g.,: • Auditing / certification • Technology licensing

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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 for 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

Key enabler (OEM & Project Development)

Key enabler (EPC)

Key enabler (Transport & Storage, Offtake)

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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DAC | Raw Materials

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

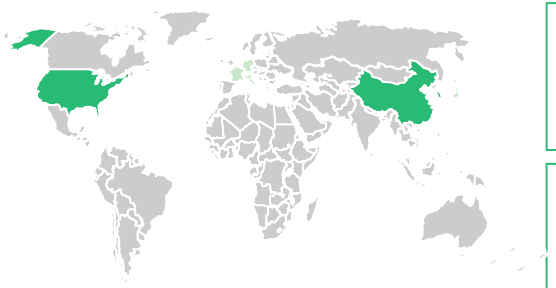
Solid sorbent: Alkanolamine polymers for amine-based coating (made from amines and alkylene oxide)
Liquid solvent: Potassium and/or sodium hydroxide solutions

N/A
Cumulative APS
U.S. SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	*Incorporated in OEM*			
Margin (%)				

GLOBAL PLAYERS - COUNTRIES



🟩 > 20% KOH or NaOH production[1,3]
▨ 10-20% KOH or NaOH production[1,3]

COMPANIES

Alkanolamines (sorbent)

AIR PRODUCTS
SIGMA-ALDRICH

KOH/NaOH (solvent)

Shin-Etsu
OXY
UNID (주)유니드
DOW
ERCO Worldwide

VALUE PROPOSITION

Widely-available and cheaply-produced alkali/alkaline earth hydroxides are essential for liquid DAC, though present little opportunity for durable competitive advantage. Though regularly produced, initial chemicals for solid sorbent are not currently to scale or tailored appropriately for DAC. Customization and increased efficacy of sorbents (big unlock) falls under OEM for development of solid sorbent technology.

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	**Solid:** access to processed alkanolamines and plastics for sorbent	M
	Liquid: access to widely-available hydroxides (e.g., Global production of KOH is dominated by the US, 27%, and China, 24%)[1]	L
Providers/supplier concentration	Consistent access to fit-for-purpose components (especially for solid sorbent), currently from few suppliers partnered with OEMs	M
Relevant infrastructure potential	Alkylene oxides and amines chemical production process is well-established and cost-effective[2], but existing production is not yet at the scale needed for DAC	L

1. ReportLinker 2. Vega et al 2017 3. World Bank
Source: BCG Analysis

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DAC | OEM

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

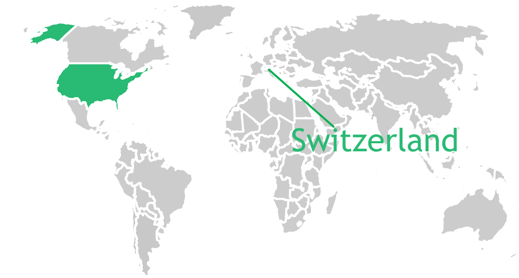
Chemical and mechanical equipment for carbon capture: air contactor fans
Solid: chemical production of alkanolamines-based structures, which require further development to improve sorbent lifetime and overall carbon capture efficiency; **liquid:** alkali/alkaline earth metal hydroxides
Plant design for improved heat regeneration and overall improved energy efficiency

$120 - 145B
Cumulative APS U.S. SAM ($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0-2	1-5	25-35
Margin (%)[1]	-	10-15%	10-15%	10-15%

GLOBAL PLAYERS - COUNTRIES



🟩 Known OEM operators

COMPANIES

climeworks

Heirloom

Partnered

SPX

Carbon Engineering

Global Thermostat

VALUE PROPOSITION

Opportunities exist to create defendable and high value IP, given de-risked financing for R&D. Improved efficiency of carbon capture technology is critical for developing DAC at scale. Current sorbents have short lifetime and inefficient carbon capture. Sorbents and solvents also must be heated to release captured carbon; R&D could reduce solid/sorbent temperature requirements for carbon release or increase plant regeneration of heat and, by extension energy requirements. Capture also relies on mechanical fans, but plant design optimization can reduce energy needs (e.g., Heirloom's passive capture). High quality solid sorbents can be exported and technology for sorbent development and plant design can be exported.

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	**Solid:** Access to fit-for-purpose components (i.e., solid sorbent or Climeworks air contactor fan[2]) **Liquid:** Access to widely-available hydroxide solutions	L
Providers/supplier concentration	4 dominant players in OEM: Climeworks, Carbon Engineering, Sustaera, & Global Thermostat, with ~dozen smaller and emerging players based on next-generation technologies (many in the U.S.) that could unlock DAC potential at scale with lower energy and facility footprint requirements	M
IP & relevant technical expertise availability	R&D opportunity to create IP to: • increase CO2 capture and lifetime of both solid sorbent & liquid solvent • increase DAC energy efficiency (energy currently is 10-33% CapEx)[3]	H
Financing access	Government and private financial support needed for R&D of carbon capture technologies Funding to improve quantity of affordable, renewable heat energy (e.g., geothermal for Climeworks)	H

---

1. Expert reported margins for low-carbon hydrogens, as a proxy for DAC OEMs 2. Expert interview 3. BCG analysis
Sources: Climeworks, Carbon Engineering, Keith et al 2018, BCG analysis

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DAC | Project Development

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Development & coordination, including site selection, permissions & contracting (EPC, operators), initial designing/engineering for facility planning, securing financing, ensuring access to affordable energy

VALUE PROPOSITION

DAC facility site selection/development should look to capitalize on areas with the right combination of favorable geographic conditions. Affordable, renewable energy access and streamlined permitting will enable early and rapid development. Project development expertise and operation can both be exported.

$50 - 65B
Cumulative APS U.S. SAM ($B, '20-50)

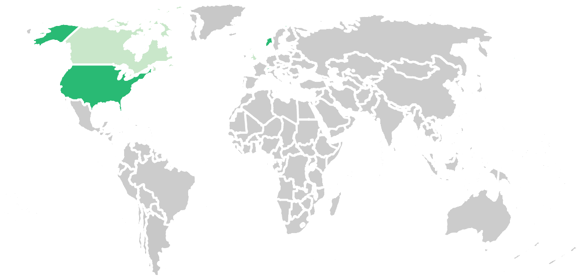
MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0-0.5	0.5-5	10-15
Margin (%)[1]	-	~15-20	~15-20	~15-20

EVALUATION

Market	Competitive Advantage	Societal Impact

GLOBAL PLAYERS - COUNTRIES



🟩 >1 facility by 2026

🟩 <1 facility by 2026

COMPANIES

climeworks

Sustaera

Carbon Engineering

1POINTFIVE

Limited data available for PD providers due to nascency of development[3]

COMPETITIVE ADVANTAGES

Input material availability & concentration	Large, uninhabited space for DAC facilities (footprints of 1—60 football fields)[1,2] with optimal environmental conditions (heat/humidity); access to affordable, renewable energy Liquid solvent plants require access abundant freshwater	H
Existing regulatory env. supportiveness	Streamlined, favorable permitting process for carbon storage will speed time to plant launch	H
IP & relevant technical expertise availability	Management and logistical expertise in setting up large industrial chemical facilities; knowledge of ideal sites	L
Market ecosystem maturity	Centralized, standardized RFP process for awarding contracts would increase opportunities for smaller-scale OEMs/startups to plan and deploy DAC projects	M
Relevant infrastructure potential	Access to affordable, renewable energy for plant operations and access to heat energy for solvent/sorbent regeneration	H

---

1. Fasihi et al 2019 2. Beutller et al 2019 3. Many OEMs currently fulfill the project development stage

Sources: Expert interviews, BCG analysis

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DAC | Financing

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Financing DAC development, which includes for OEM R&D (to increase capture and energy efficiency) and supporting largescale DAC facility creation

VALUE PROPOSITION

De-risking the funding of R&D for DAC facilities would allow for increased facility carbon capture and energy (electric for fans & heat energy for regeneration of sorbents/solvents) efficiency. Countries with more abundant and less risky financing will attract more DAC and relevant infrastructure development.

$40 - 55B
Cumulative APS U.S. SAM ($B, '20-50)

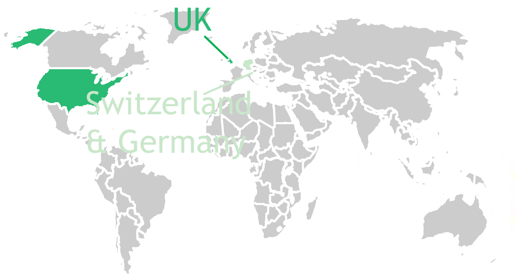
MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0-0.5	0.5-5	10-15
Margin (%)[2]	-	8-12	8-12	8-12

EVALUATION

Market	Competitive Advantage	Societal Impact
Low	Medium	High

GLOBAL PLAYERS - COUNTRIES



🟩 Government funding provided
🟩 Private funding only

COMPANIES

Breakthrough Energy
NPL
stripe
XPRIZE
RUSHEEN
THIRD DERIVATIVE

COMPETITIVE ADVANTAGES

Existing environmental regulatory support	Government tax credits, grants, and favorable interest loans can support necessary IP development and expansion of renewable energy US IIJA provides $11.6B in committed public funding for DAC through 2026[1]	M
Cost advantage potential	Financing has preference for domestic operators in its support of DAC development technology & facilities	M
Financing access	Short-term: decreased cost of capital from public and private entities supports R&D for increased carbon capture and energy efficiency Long-term: financing will reflect more standard utility loans, at which point there will not be an apparent competitive advantage	M

1. Infrastructure Investment & Jobs Act 2. Margins represent ranges for typical U.S. utility cost of capital

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DAC | EPC (Engineering, procurement & construction)

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Major DAC players have 2 main strategies for EPC: outsourcing to 3rd party project and asset services (e.g., Worley with Carbon Engineering) or in-house EPC to protect IP (Climeworks)

$250 - 310B
Cumulative APS U.S. SAM ($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0.5-5	3-5	55-75
Margin (%)[1]	~5-10	~5-10	~5-10	~5-10

GLOBAL PLAYERS - COUNTRIES

Insufficient data due to nascency of technology

COMPANIES[2]

climeworks

Worley

Worley subcontracted through 1point5, the project developer for Carbon Engineering for US 1Mt facility (2024)

VALUE PROPOSITION

OEMs (and partnered project developers, if applicable) will typically own the highest-value engineering and procurement portions of EPC, while the construction will be done by qualified local/regional EPCs with industrial facility construction experience. Preferred partner EPCs may emerge as they develop capabilities for DAC (e.g., Worley). Incentives for EPC players like tax credits could encourage EPC contracts on riskier clean technology projects (like DAC)

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Providers/suppliers concentration	The highly-concentrated OEMs are very involved in eng. & procurement. A fragmented market of EPC players exists in industrial/chemical asset services for contracting out construction, though there is potential for DAC construction specialization	H
IP & relevant technical expertise availability	Site eng. design will typically involve OEMs and would require significant technical knowledge for effectively repurposing and connecting existing industrial components (for liquid DAC) or for novel assembly (for solid DAC)	H
Trained/skilled labor force availability	DAC facility creation will require some certified/specific types of labor (as in refineries), though some required labor is standardized and easier to access (e.g., cement)	M
Market ecosystem maturity	Established bidding processes and market for EPC outsourcing for industrial and chemical asset creation	L
Financing access	Government de-risking for EPCs, as opposed to typical construction loans, in such a nascent technology can incentivize DAC facility creation in different geopolitical regions	M
Pricing advantage potential	Given labor intensity, local variations in labor costs can provide some degree of competitive advantage. Experienced EPCs may reduce costs by avoiding delays/budget overages	M

1. Margins from major EPC in wind & solar 2. Many OEMs currently fulfill the EPC requirements
Sources: BCG analysis

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DAC | Energy Inputs

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

High energy requirements for DAC includes both electricity (e.g., pumps, air contactor fan motion) and heat (higher heat and greater cost for liquid solvent vs. solid sorbent regeneration)

VALUE PROPOSITION

Affordable, renewable, co-located energy inputs are essential for DAC scaling, efficacy, and overall profitability, as they would reduce operating costs and increase net carbon capture (no additional CO2 emissions from energy use). Transmission costs for high energy inputs can be minimized by co-location of an RE source with a DAC facility

$1.1 - 1.4T
Cumulative APS U.S. SAM ($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0.5-5	10-15	330-410
Margin (%)	*Not applicable*			

EVALUATION

Market	**Competitive Advantage**	Societal Impact

COMPETITIVE ADVANTAGES

Providers/suppliers concentration	RE providers are relatively fragmented, with varying prevalence in different geographic and geopolitical regions. However, opportunity exists for providers to develop competitive advantage by specializing to support DAC's electricity and heat energy needs	M
Trained/skilled labor force availability	RE facility development and linkage to DAC facilities will require some certified/specific types of labor (e.g., project developers, electricians), though some required labor is standardized and easier to access (e.g., solar panel maintenance)	L
Market ecosystem maturity	Established bidding processes and market for RE providers to develop energy facility collocated with DAC plant	M
Pricing advantage potential	Variations in energy costs could provide some degree of competitive advantage for different RE players. Experienced RE developers may also reduce costs by avoiding delays/budget overages during facility creation	H
Relevant infrastructure potential	Increased supply and geographic spread of availability of renewable energy to ensure consistent energy access. Co-location of DAC facilities with energy sources reduces transmission costs (e.g., with Climeworks Orca facility)	H

GLOBAL PLAYERS - COUNTRIES


Insufficient data due to nascency of technology

COMPANIES

Partnered

on climeworks

Ørsted

NEXTera ENERGY

Vestas

SIEMENS energy

Sources: BCG analysis

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DAC | Operations & Maintenance

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Chemical needs for ongoing operations (alkali/alkaline earth metal hydroxides for liquid)

Equipment maintenance and replacement for continued operation of DAC facility (e.g., air contactor fans, calciner)

VALUE PROPOSITION

Certain fit-for-purpose items for replacement have limited suppliers, though there is generally high fragmentation of O&M and raw material providers for industrial facilities (though not DAC-specific)

$40 - 55B
Cumulative APS U.S. SAM ($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0-0.5	0.5-5	10-15
Margin (%)	-	~5-10	~5-10	~5-10

EVALUATION

Market	Competitive Advantage	Societal Impact

GLOBAL PLAYERS - COUNTRIES


Insufficient data due to nascency of technology

COMPANIES

Valmet

Not exhaustive (or representative of monopoly) - limited data available for O&M providers for DAC due to nascency of development

COMPETITIVE ADVANTAGES

Providers/supplier concentration	O&M providers that perform routine cleaning and parts replacement for industrial facilities are relatively fragmented	L
Trained/skilled labor force availability	More complex parts of DAC facility require trained operators (e.g., main components for liquid DAC that are from chemical plants)	M
Market ecosystem maturity	Established market for connecting O&M providers with industrial facilities could be used for DAC	L
Relevant infrastructure potential	Increased supply and geographic spread of availability of renewable energy to ensure consistent energy access. Co-location of DAC facilities with energy sources reduces transmission costs (e.g., with Climeworks Orca facility)	M

Sources: BCG Analysis

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DAC | Transportation & Storage

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

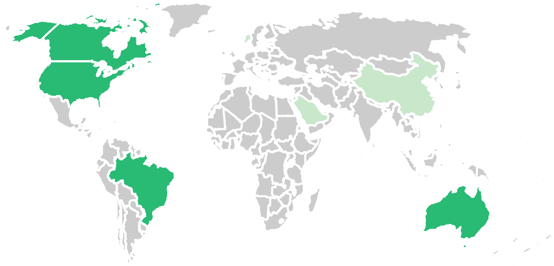
Predominantly, local transportation at DAC hubs (pipelines and pumps) and long-term geological carbon storage. Future use may include CO2 transport for industry use in products like synthetic fuels or building materials.

$125 - 155B
Cumulative APS U.S. SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0-0.1	1-5	35-45
Margin (%)	10-20%	10-20%	10-20%	10-20%

GLOBAL PLAYERS - COUNTRIES



🟩 > 10% current carbon storage/year

▩ 1-10% current carbon storage/year

COMPANIES

DAC

Carbfix

STOREGGA GEOTECHNOLOGIES

climeworks

CCUS

drax

equinor

OXY Occidental Petroleum

US operators ~50% annual global carbon storage (CC&S, currently)

VALUE PROPOSITION

Safe, long-term carbon storage will provide most revenue generation for DAC (via offsets), so geological potential and regulatory support for storage creates a distinct advantage.

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	Availability of geological storage (e.g., saline aquifers, depleted oil reservoirs) for storing captured CO2	H
Trained/skilled labor force availability	Labor needed to service DAC hub transportation infrastructure and effectively send compressed CO2 to long-term storage	M
Existing regulatory env. supportiveness	Favorable and streamlined permitting process for CO2 injection, established monitoring criteria Publicly-underwritten, long-term carbon storage to encourage offtake by decreasing risk for voluntary offset purchases (guaranteeing maintenance and auditing of storage)	H
Market ecosystem maturity	Sequestration is largely regionally-focused, though there are international operators	L
Relevant infrastructure potential	Pipeline infrastructure for transport of captured carbon	L

1. Statista Capacity of Operational Large-scale CC&S 2021
Sources: BCG Analysis, Expert Interviews

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DAC | Offtake

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

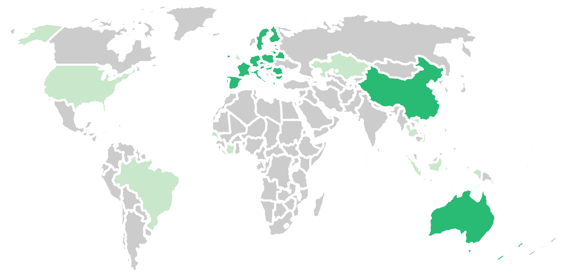
End use of captured CO2 as a carbon offset (stored) and, to a much lesser extent, other end uses (e.g., EOR and synthetic fuels, which would require conversion)

$1.5-1.8
Cumulative APS U.S. SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	-	0-5	15-20	410-510
Margin (%)	*Not applicable*			

GLOBAL PLAYERS - COUNTRIES



🟩 Established (inter)national certification market

▨ Private or local certification market

COMPANIES/COUNTRIES

Govt-Supported Market

European Commission, Australia, California Air Resources Board

Private Market

BARCLAYS, HORIZONS ETFs by Mirae Asset, KraneShares

VALUE PROPOSITION

Established carbon markets and government incentives/requirements for offsets by emitters will support revenue generation from DAC via offsets. Further development of CO2 utilization can provide an additional, though lesser revenue stream.

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Government incentives/requirements for carbon offsets by emitters & explicit acceptance (and/or preference) for DAC offsets as "high quality", permanent, quantifiable offsets Potentially de-risking long-term offset guarantees of companies to ensure quality of carbon offset even if smaller companies go out of business (e.g., 1000-year storage minimum set in RFP by Stripe[1]; government could assume liability after 50/100 years)	H
IP & relevant technical expertise availability	Mature processes for utilizing CO2 (e.g., enhanced oil recovery, synthetic fuels, building/construction materials)	L
Market ecosystem maturity	Established marketplaces for verified carbon offset purchases	M
Pricing advantage potential	Lower priced DAC offsets (with scaling) that match the broader market will be competitive and offer more permanent offset	H

---

[1] Stripe Spring 2021 Request for Projects

Sources: EU Commission Exchange-Traded Fund for carbon credits, California Air Resources Board, BCG Analysis

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DAC | Support Services

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Carbon offsets: Verification of DAC produced carbon offsets via certification for tons CO2 captured; nationalized (or broadly adopted private) standards for DAC offset quality; digital services to support carbon marketplace

Auditing: ongoing auditing for fugitive emissions from facility or CO2 leakages from storage

N/A

Cumulative APS U.S. SAM ($B, '20-50)

MARKET DYNAMICS

	2021	2030	2040	2050
APS U.S. SAM ($B)	*Not applicable*			
Margin (%)				

GLOBAL PLAYERS - COUNTRIES COMPANIES/COUNTRIES

Not applicable

Due to the nascency of commercial-scale DAC, there are insufficient data to use for projecting support service offerings

VALUE PROPOSITION

Regulations for emissions and leakage auditing for DAC will require specialized auditors and presents an opportunity for development of lower cost, remote and digital techniques for emissions monitoring. Further, large, private carbon offset verifiers have high prices for verification, which leaves gaps for smaller companies.

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Nationalized standards for verification and auditing would ensure DAC offset quality, systematize sales, and establish universal baselines for DAC carbon storage for all OEMs/ project developers to meet (e.g., EU Carbon Capture & Storage Directive 2009 requires monitoring for injected CO2 migration and leakage)[1]	L
Providers/supplier concentration	Fragmented, but a few larger, globally-adopted verifiers (e.g., Verra's Verified Carbon Standard, 870 million carbon units issued since 2007)[2], though many companies buying voluntary DAC offsets set their own, very stringent standards (e.g., Stripe requiring 1,000-year permanence)[3] Currently no centralized standard, presenting an opportunity for DAC-specific, high-quality verifiers). Private entities face high costs for verification so cannot serve clients with lower budgets Fragmented, abundant market for auditing for CO2 leakages and fugitive emissions from industrial facilities Fragmented, abundant market of IT technicians who could maintain digital verification records & system	L
IP & relevant technical expertise availability	Potential exists to develop lower cost, remote techniques for emissions monitoring (e.g., satellite remote sensing, software) leveraging computer scientists, which could be a high margin exportable service	M
Trained/skilled labor force availability	Trained auditors for fugitive emissions are needed. Current specialized audit providers for similar industrial facilities (e.g., oil & gas) can be leveraged Law professionals able to advise on securing permits for carbon storage (e.g., navigating US 45Q permits)	M

1. Verra Registry 2. Office Journal of the EU 2. company website, expert interviews
Sources: BCG analysis

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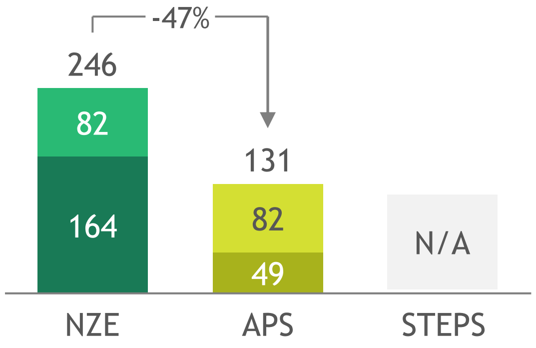
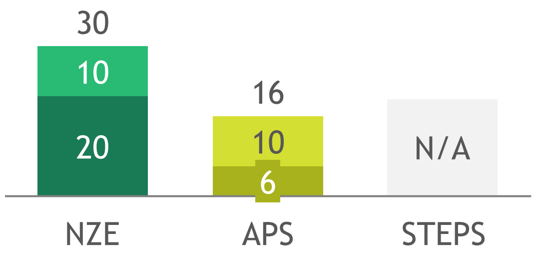
DAC | OEM offers strongest U.S. market opportunity across scenarios, though export potential falls ~40-50% from the NZE scenario

OEM

U.S. Serviceable Addressable Market (SAM)
(2020 - 2050, $B)



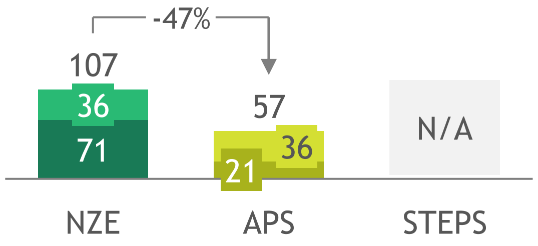
U.S. SAM Margin Pools
(2020 - 2050, $B)



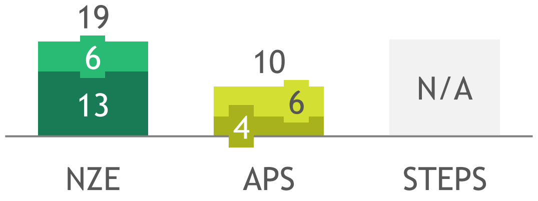
~10 - 15%[1] Est. gross average margin

Project Development

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



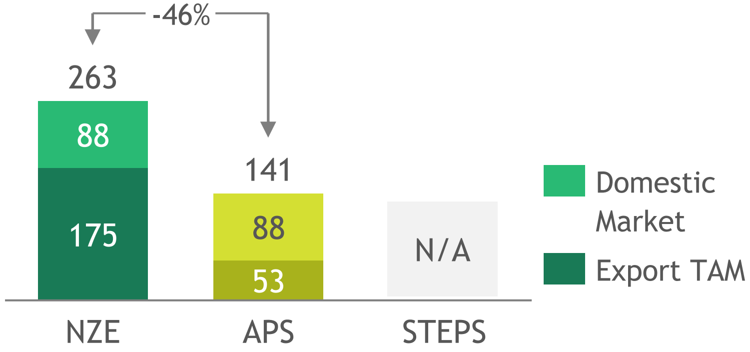
U.S. SAM Margin Pools
(2020 - 2050, $B)



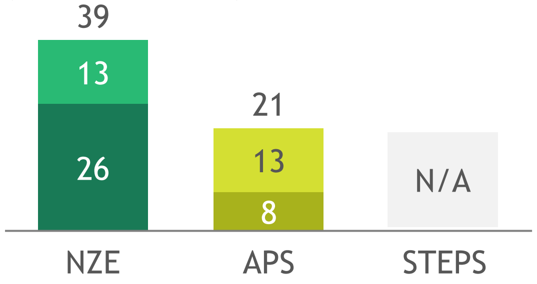
~15 - 20% Est. gross average margin

Transportation & Storage

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



U.S. SAM Margin Pools
(2020 - 2050, $B)



~ 10 - 20 % Est. gross average margin

1. Margins based on OEM margins for low-carbon hydrogen

Source: BCG analysis

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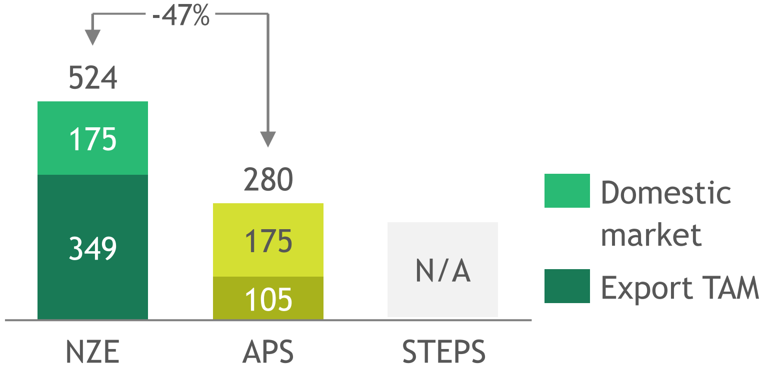
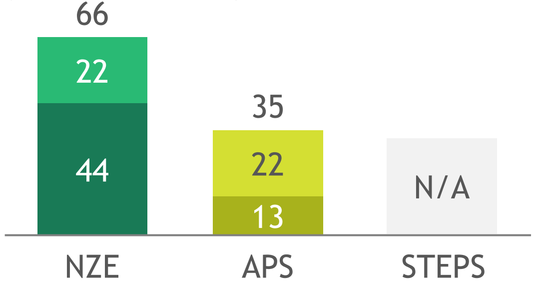
DAC | EPC offers strong U.S. market opportunity in the NZE scenario, with a ~50% drop in export potential to the APS scenario

EPC

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



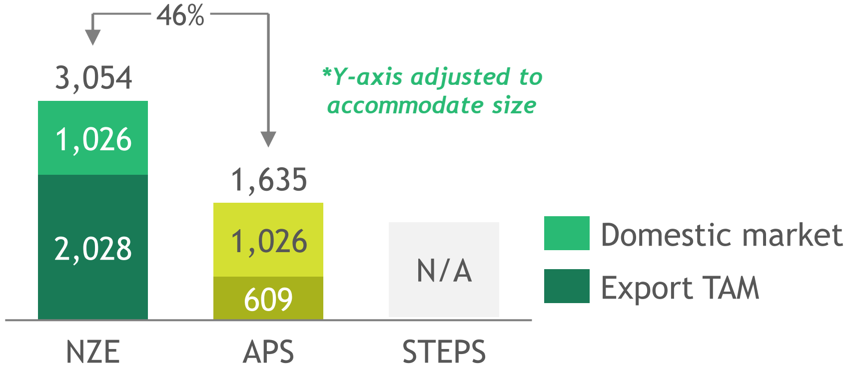
U.S. SAM Margin Pools
(2020 - 2050, $B)



~10 - 15% Est. gross average margin

Offtake

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



Y-axis adjusted to accommodate size

U.S. SAM Margin Pools
(2020 - 2050, $B)

Not applicable

N/A Est. gross average margin

Source: BCG analysis

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OEM| NZE scenario has ~2x expected market size of APS in 2050

By 2050, U.S. accounts for 27% of SAM, while E.U. and Middle East account for ~16% and ~20%

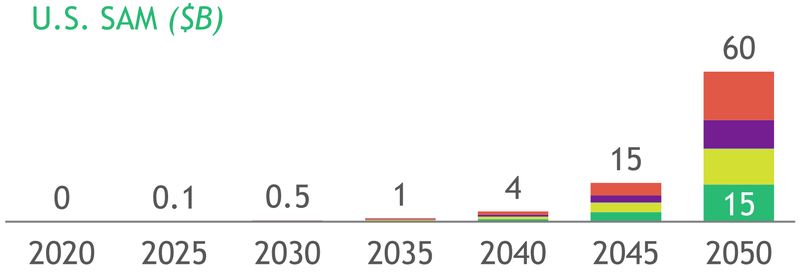
Net Zero Emissions Scenario

🟥 U.S. 🟪 E.U. 🟦 U.K. 🟨 Middle East 🟩 Rest of World

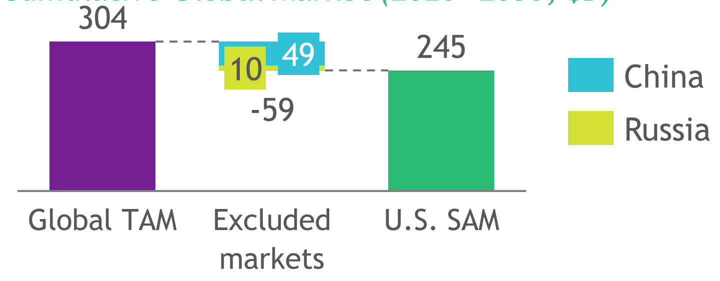
$245B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*

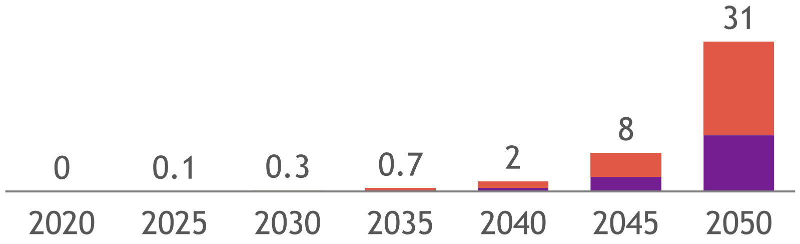


Announced Pledges Scenario

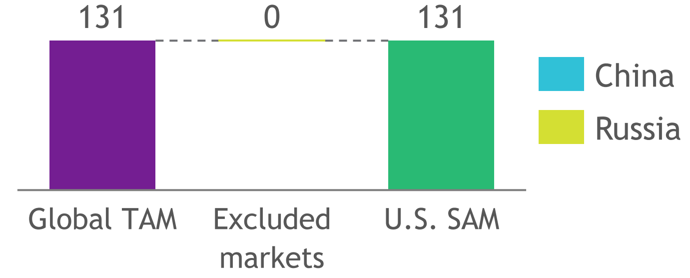
$131B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



Stated Policies Scenario

N/A – negligible uptake of DAC under STEPS scenario

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[1] Includes both U.S. domestic market and total export TAM

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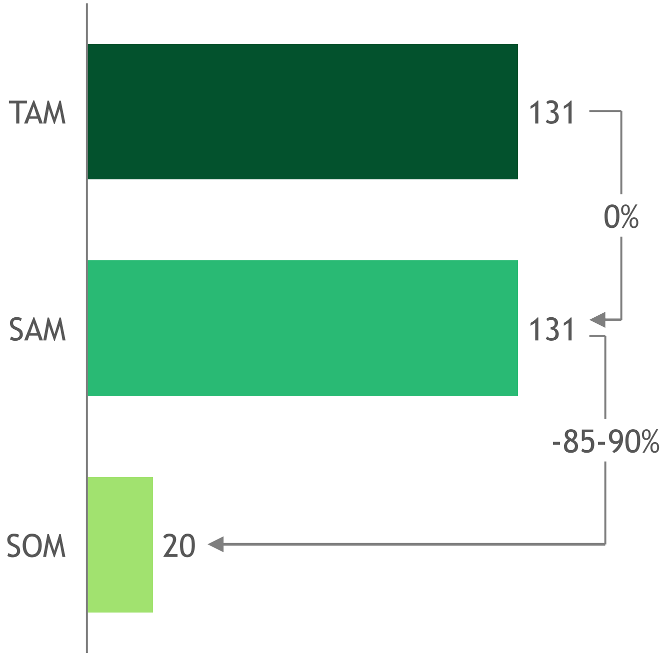
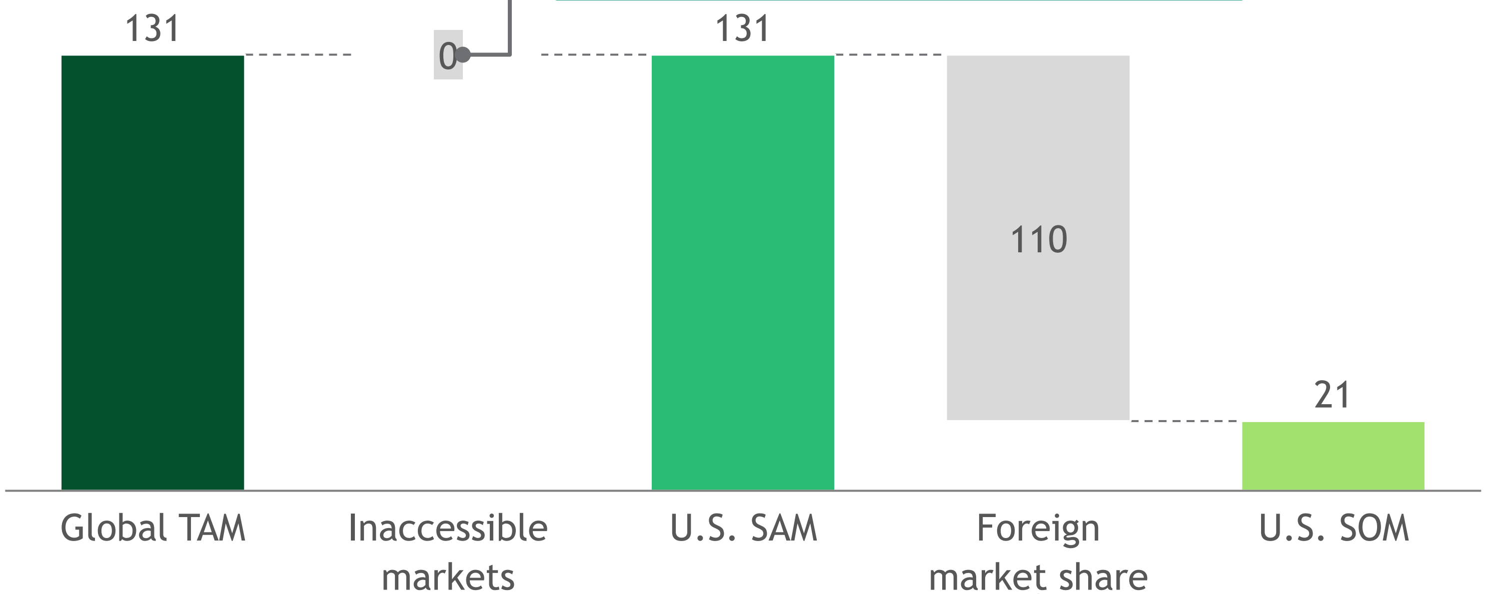
OEM | U.S. share of Direct Air Capture manufacturing of ~15 – 25% implies a moderate U.S. SOM of ~$15 - 20B through 2050 for DAC OEM

APS market sizing metrics

Cumulative market value, 2020 – 2050 *($B)*



Walk from TAM to SOM under APS scenario ($B)



Neither country noted for exclusion (China & Russia) will have a significant market for DAC by 2050 under APS

Based on analogous industries, e.g., U.S. share of global low-carbon hydrogen

Source: IEA; Shavegh et al 2021; BCG analysis

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Project Development | Market value is expected to peak 2045-2050

U.S., E.U., and U.K. retain value outside NZE, while other markets become negligible

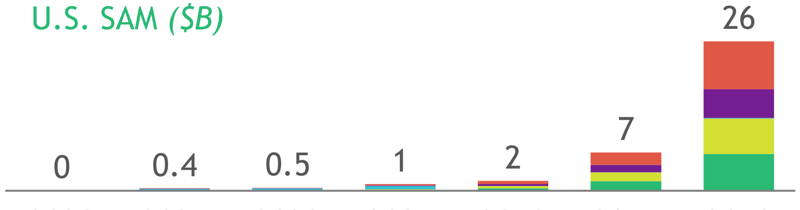
🟥 U.S. 🟪 E.U. 🟦 U.K. 🟨 Middle East 🟩 Rest of World

Net Zero Emissions Scenario

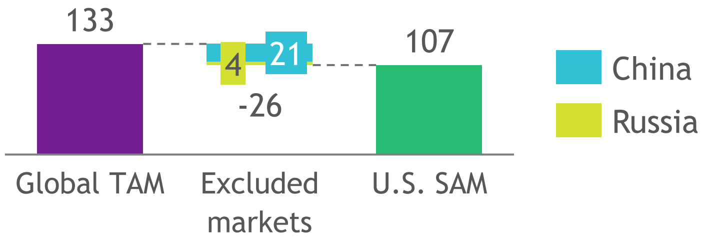
$107B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



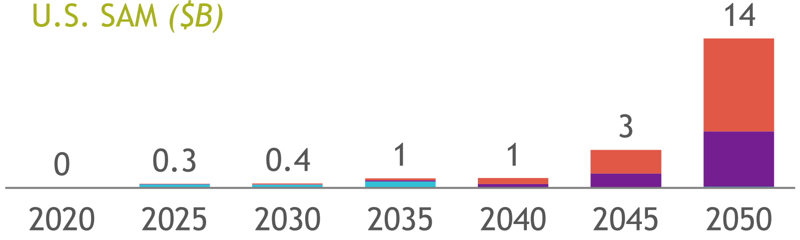
Middle East, China, and RoW lose all value outside of NZE, while U.S., E.U., & U.K. retain value

Announced Pledges Scenario

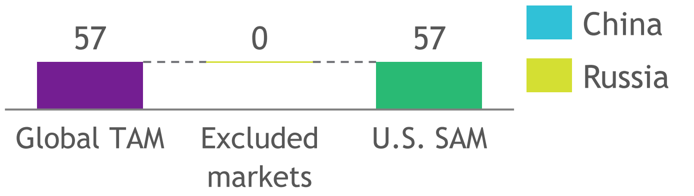
$57B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020- 2050, $B)*



Stated Policies Scenario

N/A – negligible uptake of DAC under STEPS scenario

[1] Includes both U.S. domestic market and total export TAM

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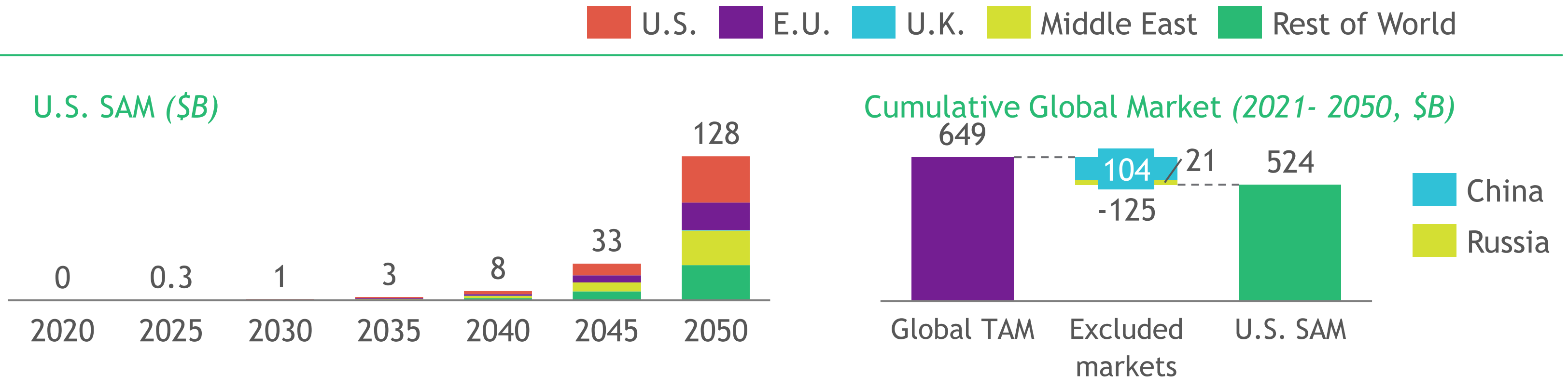
EPC | Market value is expected to peak 2045 – 2050 across scenarios

In NZE scenario only- EPC for Middle East is likely relevant for U.S. export

Net Zero Emissions Scenario

$524B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 – 2050)*



U.S. SAM *($B)*

Cumulative Global Market *(2021- 2050, $B)*

Announced Pledges Scenario

N/A – negligible market for exporting EPC capabilities (negligible Middle East region market)

Stated Policies Scenario

N/A – negligible uptake of DAC under STEPS scenario

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Transport & Storage | Market value is expected to peak 2045 – 2050

U.S. & E.U. retain value outside NZE, with small, consistent U.K. market (<0.2% domestic US market)

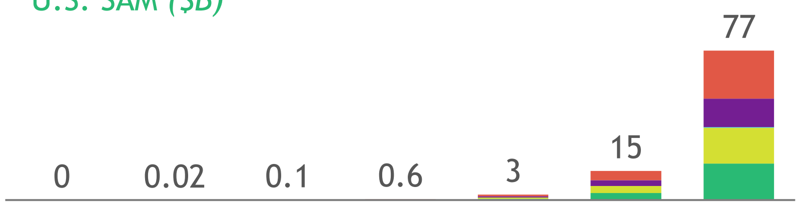
Net Zero Emissions Scenario

🟥 U.S. 🟦 U.K. 🟩 Rest of World
🟪 E.U. 🟨 Middle East

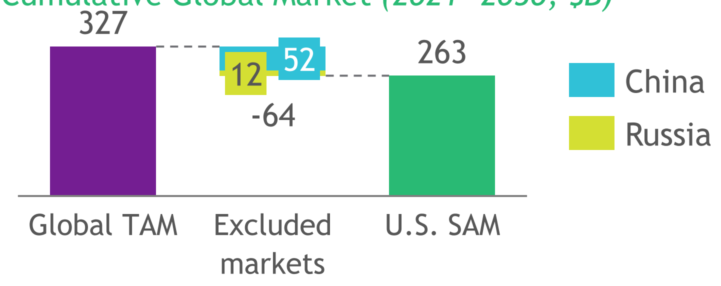
$263B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2021- 2050, $B)*



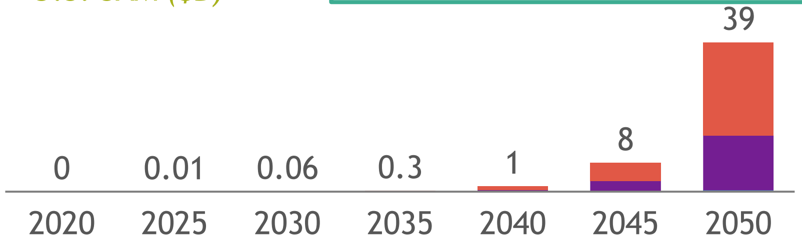
Announced Pledges Scenario

Middle East, China, and RoW lose all value outside of NZE, while U.S., E.U., & U.K. retain value

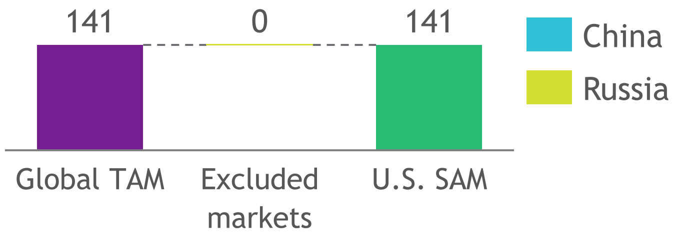
$141B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2021- 2050, $B)*



Stated Policies Scenario

N/A – negligible uptake of DAC under STEPS scenario

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1. Includes both U.S. domestic market and total export TAM

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Offtake | Market value is expected to peak 2045 – 2050 across scenarios

U.S. & E.U. retain value outside NZE, with small, consistent U.K. market (<0.2% domestic US market)

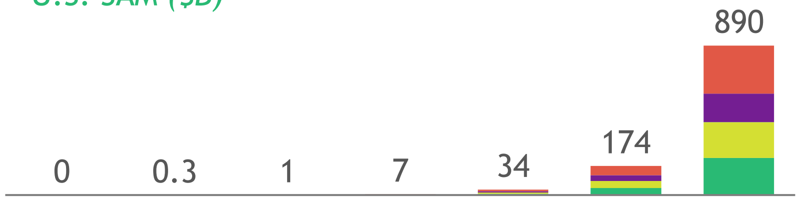
🟥 U.S. 🟪 E.U. 🟦 U.K. 🟨 Middle East 🟩 Rest of World

Net Zero Emissions Scenario

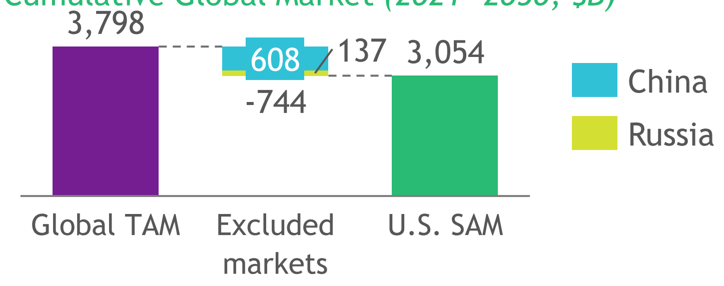
$3T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 – 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2021- 2050, $B)*



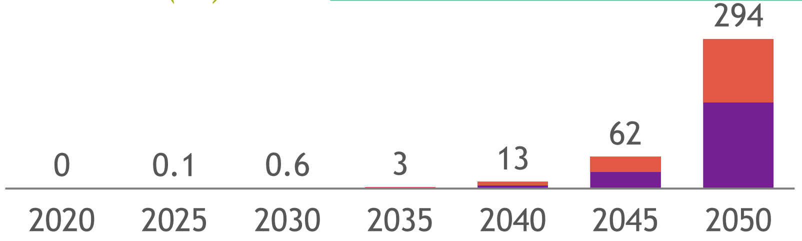
Middle East, China, and RoW lose all value outside of NZE, while U.S., E.U., & U.K. retain value

Announced Pledges Scenario

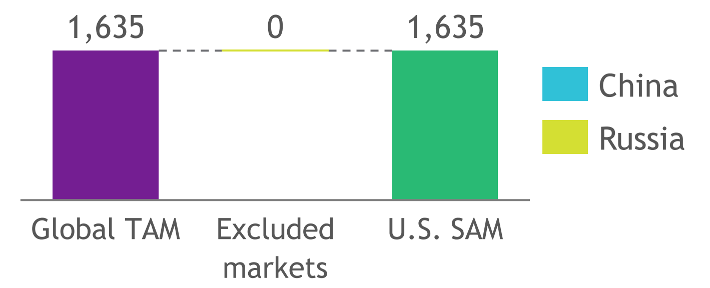
$1.6T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 – 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2021- 2050, $B)*



Stated Policies Scenario

N/A – negligible uptake of DAC under STEPS scenario

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[1] Includes both U.S. domestic market and total export TAM

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OEM | U.S. has strong innovation, dedicated public funding and workforce, but Europe leads investments, policies & DAC deployment

☆ = *Key dimension*

	Areas for Competitive Advantage	Ranking	Summary analysis
	Raw material availability	High	- U.S. is a leader in chemical production for liquid DAC, though production is not currently at scale to meet growing DAC needs. Solid sorbent DAC uses a variety of chemicals, most of which are not currently produced at scale needed (e.g., amine-based structures)
☆	**Intellectual Property & innovation**	High	- U.S. 1st globally in patent volume in DAC innovation (predominantly for carbon capture medium), followed by China at 1/3 of U.S. - Historic OEM Climeworks leads patenting activity (~2x next leader), but 5 of top 12 patent-producing companies are U.S.-based - The design and manufacturing of carbon capture mediums and energy efficient DAC facilities is complex, creating a steep learning curve for DAC. Novel designs and chemical mediums can have major impacts on the efficacy and costs of carbon capture (e.g., energy use, medium durability), making IP the most impactful area in these segments
	Research & technical leadership	High	- U.S. has the highest literature publication rate for DAC chemical media (~25% greater than China) and 40% of global leading research institutes in DAC research are in the U.S.
☆	**Cost advantage potential**	Low	- Lowest cost and highest efficacy carbon capture medium are likely to be adopted by global DAC leaders to move down the cost curve and expand DAC uptake to meet net zero goals - Labor is a small fraction of OEM costs (estimated ~15%), so there would be no significant advantage to low vs. high income countries in OEM
☆	**Demand / supply side policy**	Low	- U.S. has no demand side policies in place, though 2 are proposed: Federal Carbon Dioxide Removal Leadership Act of 2022 & SEC Scope 3 emissions reporting. Comparable economies, U.K. and E.U. already have public DAC procurement agreements
	Market maturity[1]	High	- Private investments are predominantly made in OEMs. U.S. has 2nd highest private investments, but at only ~25% the level in Switzerland, the leading country - U.S. leads public funding directly for DAC ($11.7B), though E.U. leads public funding that for climate technology solutions that could be used to fund DAC R&D (~$130B)
	Ecosystems / infrastructure	N/A	- Not applicable in this segment - OEMs require laboratories and pilot testing sites for R&D, but this would be individually-created
	Overall ranking		U.S. has a **potential to build a durable competitive advantage**, due to growing activity of US-based and US-operating OEMs and high market maturity relative to others; however, a gap in regulatory support and a slight lag in investments risk long-term leadership potential through next-generation OEMs

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[1] Due to the importance of public funding for DAC as a nascent industry, public funding is incorporated in market maturity for DAC. This section highlights where public funding is being used similarly to private investments to support DAC development & scaling

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Project Development | U.S. has publicly-funded infrastructure, critical resources, and experience, though lacks policy support

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	- Not applicable in segment
Intellectual Property & innovation	High	- Effective systems integration is critical, especially for liquid DAC, which repurposes existing equipment for DAC. U.S. will have the first large liquid DAC facility (1 MtCO2 planned by 2024 in Permian Basin), so will gain early learning & expertise to streamline development and lower costs
Research & technical leadership	High	- Experienced project developers for industrial chemical facilities (e.g., EOR, oil & gas, CCUS) can streamline and accelerate design and deployment of commercial-scale DAC facilities, including securing permits for storage
☆ **Cost advantage potential**	High	- U.S. has strong potential to develop co-located, affordable RE (e.g., solar, wind) or low carbon energy to support DAC facilities - Of the major producers of DAC (U.S., Switzerland, E.U., and U.K.), the U.S. has the highest labor costs, which is ~70% of PD costs
☆ **Demand / supply side policy**	Low	- U.S. has no demand side policies in place, though 2 are proposed: Federal Carbon Dioxide Removal Leadership Act of 2022 & SEC Scope 3 emissions reporting. Comparable economies, U.K. and E.U. already have public DAC procurement agreements - California has implemented the Low Carbon Fuel Standard, which encourages purchase of carbon credits (DAC included)
Market maturity[1]	High	- U.S. is the only country funding DAC hubs and directly funding R&D and design work for DAC development and scaling (~$90M) - Private investments for OEMs support early-stage, small-scale (order of ktCO2) DAC development, though commercial DAC will likely be funded by traditional project development sources (e.g., bank loans). U.S. has 2nd highest private investments, but at only ~25% the level in Switzerland, the leading country
☆ **Ecosystems / infrastructure**	High	- Abundant geological storage in the U.S. supports largescale DAC deployment, but stringent environmental & permitting (e.g., Class VI) limits the pace at which DAC facilities can be developed and scaled, especially by small OEMs - DAC co-location with existing industrial facilities (e.g., oil & gas, waste recovery plants) could reduce energy demands by using waste heat and reduce expenses and logistics for novel pipelines, plumbing, roads, etc.
Overall ranking	🟩	U.S. has a **strong existing competitive advantage and should maintain it.** Advantage is due to access to critical resources, a mature market relative to others, and a strong synergistic workforce; however, Europe currently leads overall investment, and a lack of public procurement could risk an early lead in this segment

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[1] Due to the importance of public funding for DAC as a nascent industry, public funding is incorporated in market maturity for DAC. This section highlights where public funding is being used similarly to private investments to support DAC development & scaling

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EPC | US has strong workforce and engineering capability, but EPC will likely only be exported to the Middle East region

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	• Not applicable in segment
Intellectual Property & innovation	N/A	• Not applicable in segment for construction, though some engineering/procurement may be handled by OEMs/PDs
Research & technical leadership	High	• The U.S. has many EPC companies/professionals with relevant experience, though international EPCs compete in U.S. domestic market (e.g., Australian-based EPC (Worley) is contracted to develop 1Mt DAC plant in U.S. Permian Basin)
☆ **Cost advantage potential**	High	• More experienced EPCs are more likely to secure contracts due to their cost and time savings in construction. While South Korea leads global EPC revenue, the U.S. has major global EPC players (e.g., Bechtel, Fluor, KBR) • U.S. higher labor costs (~70% of EPC costs) could limit domestic use and export of EPC capabilities
Demand / supply side policy	Low	• Use of domestic EPCs can be incentivized (e.g., tax credits) for OEMs and developers and required for publicly-funded DAC projects
Market maturity	N/A	• EPC contracts are directly with OEMs/PDs and additional financing is largely not applied
Ecosystems / infrastructure	High	• Large U.S.-based EPC players have established agreements/systems for suppliers and expertise in ancillary EPC needs (e.g., securing permits), increasing overall competitive advantage for EPCs
Overall ranking	🟩	U.S. has a **potential to build a durable competitive advantage**, due to skilled, experienced EPC operators and planned early U.S. adoption of DAC, which will increase EPC learning and cost advantages. However, policies can incentivize domestic EPC contracts to secure domestic DAC leadership that could translate to global leadership with export of the most experienced, cost-effective EPC

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Transportation & Storage | U.S. has abundant resources and existing expertise that can support largescale DAC deployment

☆ = *Key dimension*

	Areas for Competitive Advantage	Ranking	Summary analysis
☆	**Raw material availability**	High	- U.S. has immense potential for geological storage (~ 810 Gt) in both saline aquifers & depleted oil wells
	Intellectual Property & innovation	High	- U.S. major oil & gas players have necessary expertise and equipment capabilities for pipeline construction/operation and subsurface injection for geological storage of gas/fluids, which will speed DAC scaling - Transportation & storage has largely standardized processes, though some techniques or equipment used by major oil & gas players for more efficient compression and gas transport may be proprietary
☆	**Research & technical leadership**	High	- U.S. has large numbers of engineers/technicians with oil & gas (e.g., experience in injection, pipelines) or other technical training (e.g., fugitive emissions monitoring and assessment) that can transfer skills to DAC - R&D and implementation of novel DAC technology requires specialized expertise that is less available globally. As the leading country for DAC research, the U.S. has a significant opportunity to develop DAC technical experts
	Cost advantage potential	High	- U.S. has low and predictable costs for CO2 storage due to abundant storage space and technical expertise and experience from synergistic industries. Despite higher labor costs, the U.S. is still currently competitive on price
☆	**Demand / supply side policy**	High	- U.S. 45Q policy provides tax credits per ton CO2 captured and stored permanently ($50/tCO2) which encourages DAC credit creation, though increased credit value would support storage for higher cost DAC vs. other carbon credits - E.U. has a comprehensive systems for increasing demand, including carbon taxes, emissions restrictions and credit trading via their Emissions Trading Scheme (ETS)
	Market maturity[1]	High	- U.S. leads public direct DAC funding ($11.7B), including specific funding for the creation of 4 DAC hubs that will include pipelines, compressors, and injection for storage
☆	**Ecosystems / infrastructure**	High	- Planned DAC hubs will provide critical publicly-funded infrastructure and synergistic expertise and equipment (e.g., oil & gas technology for CO2 subsurface injection) can be translated for use in DAC - Hub infrastructure funded in IIJA can also support DAC capture & storage, reducing costs and accelerating scaled deployment
	Overall ranking	🟩	U.S. has a **strong existing competitive advantage and should maintain it.** Advantage is due to storage potential, relevant skilled labor & technology, and a highly mature market relative to others, though more supportive policies could maintain this lead as DAC policies rapidly evolve in other countries

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1. Due to the importance of public funding for DAC as a nascent industry, public funding is incorporated in market maturity for DAC. This section highlights where public funding is being used similarly to private investments to support DAC development & scaling

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Offtake| U.S. is not currently leading, but can increase advantage through market maturity, policy, and quality standards

☆ = *Key dimension*

	Areas for Competitive Advantage	Ranking	Summary analysis
	Raw material availability	N/A	• Not applicable in this segment
	Intellectual Property & innovation	Low	• U.S. has leading startups with remote sensing and AI-based monitoring, reporting and verification • Commercial ability to use concentrated CO2 in industrial products (e.g., low carbon materials, synfuels) is currently in development in other countries (e.g., Europe, Chile, Canada). As DAC becomes economical, commercial use is expected to grow
	Research & technical leadership	High	• DAC credits/offsets must be validated and quality-assured to create buyer confidence (e.g., water, energy, and land use, impact on surrounding communities). Strong availability of skilled labor in the U.S. from synergistic industries (e.g., oil & gas, emissions compliance) will enable validation for DAC credits, following standards establishment • Sales expertise, while necessary for offtake of credits of CO2, is not a distinct competitive advantage for the U.S.
☆	**Cost advantage potential**	Low	• Producers of the lowest cost, verified DAC offsets will have competitive advantage in the global market. Prices are currently high for all OEMs, but aggressive scaling plans in the U.S. will likely decrease costs fastest (>1 MtCO2 by 2024) • Currently, only the E.U. has operational DAC, with prices largely determined by high capital & operating costs
☆	**Demand / supply side policy**	Low	• No current policies establish DAC offtake quality standards and encourage DAC offtake over other carbon credits as a high-quality quantifiable negative emission (e.g., subsidies or higher credit value). The E.U. announced plans to set standards in 2021 • Government procurement agreements are needed to de-risk current DAC offtake and encourage DAC expansion to reduce costs for the future. The E.U. and U.K. have public agreements, while the U.S. has a proposed bill (Federal Carbon Dioxide Removal Leadership Act of 2022) • The current U.S. SEC proposal for companies to report and minimize their scope 3 emissions would likely increase DAC credit demand
	Market maturity	N/A	• Not applicable in this segment
☆	**Ecosystems / infrastructure**	Low	• Bilateral trade agreements between countries are necessary for sale of DAC credits created in one country to another • E.U. leads the carbon market with an established ETS, valued at ~$100/tCO2 in 2019, which could be used for DAC • California's Low Carbon Fuel Standard allows purchase/trading of credits, but no other public state or federal carbon market exists in U.S. • In U.S., private companies have guaranteed $925M carbon removal procurement via the advanced market commitment Frontier • Various industries are projected to use concentrated CO2 (e.g., low carbon materials, synfuels), but infrastructure & market development will be needed to effectively and economically use DAC
	Overall ranking	🟩	U.S. has a potential to build a durable competitive advantage, despite not having it today. Despite available expertise and private procurement agreements, immature domestic and international markets and lacking policies to encourage DAC offtake could limit long-term leadership in this segment

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Direct Air Capture | Overview of key assumptions

Assumption	Value	Impact on Calculations	Source
NZE Global DAC Abatement by 2050	~7 Gt	Based on DAC costs projected by OEMs and overall negative emissions needs to meet climate targets, this abatement potential by 2050 assumes aggressive DAC expansion. This sets the capacity in NZE scenario and, by extension, the market size and job numbers	Goldman Sachs Carbonomics
APS Global DAC Abatement by 2050	~3 Gt	This sets capacity under APS and, by extension, market size and job numbers. Only countries with net zero by 2050 commitments and current DAC investments are projected to reach their DAC abatement for NZE. which is what this value represents.	*Expert Input*
Location of % Global DAC abatement under NZE by 2050	27% N. America, 20% Middle East, 16% E.U., 16% China, 21% RoW	These percentages determine the amount of DAC capacity achieved by each country/region if net zero by 205- is reached, which is the end point DAC capacity over time is projected from. This determines capacity, which in turn drives market values and job estimates	Shayegh et al. 2021
US % of North America DAC in 2050	~99%	The vast majority of DAC (not CCUS) in North America is expected to be built in the U.S., based on projects pledged and in progress. This percentage determines U.S. DAC capacity and, by extension, market sizing and job numbers	U.S. IIJA, Carbon Engineering
Exponential growth of DAC capacity	Exponential	As an exponential vs. linear growth for DAC, more of the capacity, CapEx, jobs, etc. are concentrated later in the time window. This is consistent with predictions of DAC capacity growth, cost efficiencies, and the delay in largescale DAC uptake until further into decarbonization efforts. This determines the rate of growth of DAC and cumulative capacity, market size, and job numbers	*Expert Input*
CapEx for 1Mt DAC facility	Solid: $1.6B ('25) →$0.4B (at 10Gt) Liquid: $0.9B ('25) → $0.15B (at 10Gt)	This sets the amount of CapEx and the DAC facility construction learning rate from increased deployed DAC capacity. This influences market size over time (as global DAC capacity increases) for OEM, Project Development, Financing, EPC, and O&M	Fasihi et al 2019 & Broehm 2015 ECTF report

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Clean Steel

Clean steel | Definition of each segment across value chain

Raw materials	OEM	Financing	EPC	Energy inputs	Operations & Maintenance		Transport	Offtake	Support Services
	Focus area		*Focus area*						
Mining of iron ore: - Exploration - Permitting - Construction - Excavation via drilling/ blasting and ore extraction - Stockpiling and transport of ore to refinery Lime & coal Crushing, grinding, blending/ concentrating, agglomeration via sintering/ pelletizing Use of scrap/ recycled steel Alloying metals (<10% of steel, not focus area) Electrolyzer inputs[1]	Production of clean smelting & steelmaking equipment, including: - **DRI** reactors for gaseous/ hydrogen-based reduction - Electric arc furnaces (**EAF**) - Advanced basic-oxygen furnace (**BF-BOF**) systems with high-efficiency features including carbon capture & utilization / sequestration (CCUS) - New, innovative steelmaking methods such as molten oxide electrolysis	Financing of steelmaking facility development & construction Private investments & loans, public markets Government incentives, grants, and loans	Energy efficiency improvements (e.g., heat regeneration, waste heat or gas recovery) EPC- new facilities 1. Ground-up construction of new plants leveraging **DRI-EAF** or CCUS technology & H2 production (including project development[2]) Retrofitting existing facilities 2. Installation of CCUS and/or top gas recovery systems for **BF-BOF** operations OR 3. Furnace replacement with **hydrogen-fueled DRI** & **EAF**, using NG as stopgap	Fuel, including: - Low-carbon hydrogen[1] - Natural gas - Renewable electricity	**Ironmaking:** Processing & reduction of ore via blast furnace or direct reduction furnace Introduction of flux & reducing agents (e.g., coke, NG, hydrogen) - **DRI:** CO & NG/H_2 - **BF-BOF:** non-cooking coal & iron pellets (COREX) OR coal & iron ore (FINEX) **Steelmaking:** Production of steel via **EAF** or **BF-BOF** & CCUS Efficiency improvements to reduce fuel consumption & waste, including... **BF-BOF:** - Gas recovery **EAF:** - Eccentric bottom tapping - Scrap preheating - Stirring gas injection **Casting:** Ingot casting **Maintenance:** Cleaning, repair, & replacement of critical plant parts (e.g., furnaces, turbines, pipes, air blast pump)	**Forming:** Includes stamping, rolling, extrusion, drawing & forging Forming can be (in decreasing order of energy/ equipment intensity): hot, room temperature, or cold **Finishing & packing:** Cleaning & pickling Finishing/ shaping processes to produce final product Unitization Palletization (adhering to international conventions)	Transport of unitized & palletized steel to distributors	Sale & distribution of clean steel to consumers	Steel collection & recycling services

1. Low-carbon hydrogen technologies are covered in a separate "Hydrogen" value chain 2. Project development is included in EPC because steel producers commonly conduct their own designing and/or contracting out to OEMs

DRI = direct reduced iron, **EAF** = electric arc furnace, **BF-BOF** = blast furnace/basic oxygen furnace, **CCUS**= carbon capture utilization & storage

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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

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Clean Steel | Raw Materials

High | Medium | Low | N/A

DESCRIPTION OF TECHNOLOGY

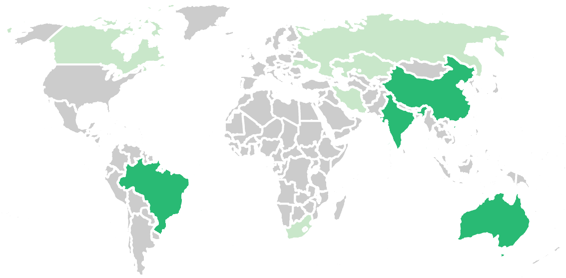
Ironmaking & steelmaking inputs: Iron ore pellets (+ sinter for BF) and limestone (commonly used as flux material to increase fluidity and reduce impurities)
Furnace: Coal (coke) (BF-BOF w. CCUS) or hydrogen[4] (H2-fueled DRI-EAF) for ore reduction
Electrolyser materials: Platinum, iridium, and nickel[4]
EAF materials: Petroleum coke and coal pitch (for synthetic graphite electrodes)

$2.1 - 2.7
Cumulative APS
U.S. SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	0	40-50	90-120	160-200
Margin[5] (%)	6-10%	6-10%	6-10%	6-10%

GLOBAL PLAYERS - COUNTRIES



🟩 > 200 Mt iron ore production
🟩 50-100 Mt iron ore production

COMPANIES

Rio Tinto
BHP
Anglo American
Vale
Teck
LKAB
FMG Fortescue

VALUE PROPOSITION

As with traditional steelmaking, managing reliable raw material supply can be a key factor in cost-competitive steelmaking. All steel production requires iron ore and flux (e.g., limestone), so countries with high mining/production capabilities will have an advantage. For BF-BOF, coal is still used (CCUS added to facility), so countries with access to affordable coal for steel production will have an advantage

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	**All:** access to iron ore and limestone. Iron ore is primarily mined in Australia, Brazil, & China[1]. Global lime production is dominated by China (~70%)[2] **BF-BOF w/CCUS:** access to coal for coke production. China produces ~50% of global coal[2]	M
Providers/supplier concentration	Iron ore production is concentrated (5 main producers) with operations in Australia, Brazil, & China[1], but geological concentration is diverse as many countries have domestic ore deposits	M
Cost advantage potential	Local/regional access to ore & processing can reduce final steelmaking costs by eliminating transportation requirements	M

1. Mining Intelligence report 2. USGS Mineral Commodity Summaries 3. NS Energy 4. Hydrogen discussed in energy inputs and electrolyzers included in hydrogen value chain 5. Highly variable based on commodity ore prices
Source: BCG Analysis

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Clean Steel | OEM

High | Medium | Low | N/A

DESCRIPTION OF TECHNOLOGY

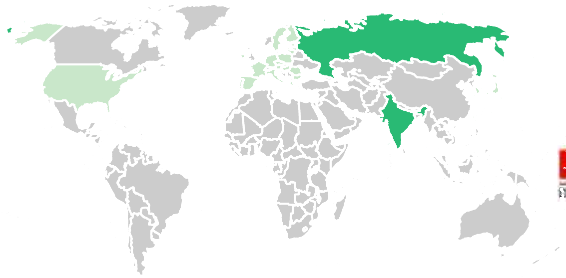
Equipment: DRI-EAF compatible with NG (stopgap) and H2, CCUS added inline to existing BF-BOF, onsite electrolyzing capabilities
Plant design: efficiency improvements to reduce fuel consumption & waste, including heat recovery, waste gas to fuel conversion, BF-BOF-specific top gas recovery, and EAF-specific eccentric bottom tapping and scrap preheating

$0.8 - 1.0
Cumulative APS
U.S. SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	0	15-20	35-45	60-75
Margin (%)	8-10%	8-10%	8-10%	8-10%

GLOBAL PLAYERS - COUNTRIES



🟩 > 10% DRI-EAF (NG fuel now)

⬜ > 30% scrap-EAF

COMPANIES

ArcelorMittal

ENERGIRON
DRI TECHNOLOGY BY TENOVA AND DANIELI

PRIMETALS TECHNOLOGIES

Torero

Steelanol

MIDREX

VALUE PROPOSITION

Clean steel OEMs need to have a proven track record of successful projects to generate commercial trust and require significant capabilities in industrial design & engineering. Plant design optimization can lead to cost advantages from reduced energy/fuel requirements (e.g., heat and fuel recovery, waste gas to fuel conversion). Technology used in CCUS, NG→H2 DRI-EAF furnaces, and onsite electrolyzing will also be increasingly incorporated into new plants

EVALUATION

Market | Competitive Advantage | Societal Impact

COMPETITIVE ADVANTAGES

Providers/supplier concentration	Semi-concentrated OEMs are developing clean steel technology, including leaders Midrex and Tenova. Some steel producers are pioneering OEM themselves (e.g., ArcelorMittal planning DRI-EAF replacement and waste gas conversion to fuel for plants in Bremen & Eisenhuttenstadt)[1]	M
IP & relevant technical expertise availability	Ongoing innovation creates can drive efficiency improvements and differences in capabilities across equipment, but time-to-market and a maturing technology will limit the impact of IP in the future	M
Financing access	Government and private financial support needed to meet high CapEx requirements to retrofit existing steel production plants or create new plants with cleaner technology (e.g., HYBRIT project to create DRI-EAF plant is a joint venture of mining and ore producer (LKAB), steelmaker (SSAB), and energy producer (Vattenfall) that is also supported by the government (Swedish Energy Agency)[2])	M
Trained/skilled labor force availability	Specialized and experienced teams are required to manufacture and install plant equipment including reactors and furnaces, with significant industrial engineering capabilities required	H

2. Company websites 2. Press release by Vattenfall
Source: BCG Analysis
DRI = direct reduced iron, **EAF** = electric arc furnace, **BF-BOF** = blast furnace/basic oxygen furnace, **CCUS**= carbon capture utilization & storage

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Clean Steel | Financing

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

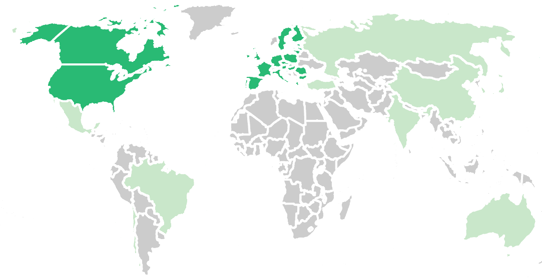
Financing of retrofits or new plant construction, both of which have high CapEx requirements and long return timelines for steel producers. Currently, financing is a combination of private (often self-funded through cashflow/equity markets) and public funding, though traditional funding of industrial asset creation (e.g., bonds & bank loans) will increase as sector matures

$95 - 120
Cumulative APS
U.S. SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	0	1-3	1-5	5-10
Margin (%)	8-12%	8-12%	8-12%	8-12%

GLOBAL PLAYERS - COUNTRIES



🟩 Public funding available
🟩 Private (company) funding only

COMPANIES/COUNTRIES

Companies

LKAB, ArcelorMittal, SSAB SWEDISH STEEL

Countries/Governments

Swedish Energy Agency, Canada, ENERGY

VALUE PROPOSITION

Because of the high CapEx needed for retrofits and new plant construction with delayed/limited returns, government financial support is currently needed to increase capacity for clean steel. Public funding in the form of joint ventures, grants, subsidies, and favorable taxes can encourage more clean steel transition. In the long-run, financing will become more traditional, as clean steel technology is further developed and more widely adopted (achieving scalability)

EVALUATION

Market	**Competitive Advantage**	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Government tax credits, grants, and favorable interest loans can support the adoption of clean steel technology in both existing and new steel production facilities by reducing capital costs & risk (e.g., Swedish Energy Agency provided 25% funding for a joint project by LKAB, SSAB, and Vattenfall to create an H2-fueled DRI-EAF facility[1])	H
Financing access	Short-term: decreased cost of capital from public funding supports adoption of clean steel technology, important for both reducing emissions and increasing efficiencies that will enable scalability of retrofitting and novel clean steel production (e.g., more effective swapping out furnaces for minimal plant downtime, increased waste gas-to-fuel conversion)	M

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[1] Vattenfall press release

Source: BCG Analysis

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Clean Steel | EPC

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

3 primary approaches for clean steel production have different EPC needs:

1. New plant construction (DRI-EAF or CCUS): traditional EPC full facility creation
2. Retrofitting BF-BOF operations: installing and integration of CCUS
3. Retrofitting for H2/NG DRI & EAF: replacement of furnace, installation of electrolyzers

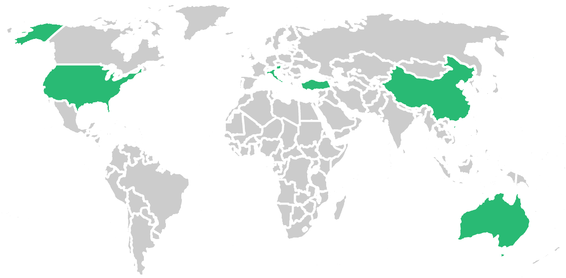
EPC is often conducted by the OEM with local contractors assisting at different phases of construction

$240-300
Cumulative APS
U.S. SAM
($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	0	5-10	10-15	15-25
Margin (%)	8-10%	8-10%	8-10%	8-10%

GLOBAL PLAYERS - COUNTRIES



🟩 Companies offering clean steel EPC services

COMPANIES

Retrofitting

IAC Industrial Accessories Company

DANIELI

SINOSTEEL

New Construction

SAIPEM

IHI

VALUE PROPOSITION

OEMs typically own the highest-value engineering and procurement portions of EPC, with contracted qualified local/regional EPCs assisting with construction. A strong track record of on-time, on-budget projects differentiates OEM/EPC players as it requires a strong background managing complex industrial engineering capital projects, with most Western steelmakers trusting only a select few OEMs

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Providers/supplier concentration	Concentrated OEMs will likely be very involved in eng. & procurement. A fragmented market of EPC players exists for contracted construction, though there is potential for retrofitting & new clean steel plant construction specialization	M
Trained/skilled labor force availability	Clean steel facility creation or retrofitting will require large amounts of specialized/certified labor, and many OEMs depend on having strong in-house teams for steel mill construction	H
IP & relevant technical expertise availability	Site eng. design will typically involve OEMs and would require technical knowledge for effectively connecting either CCUS or new DRI-EAF to existing facilities or novel creation of DRI-EAF. Construction will likely be outsourced to local EPCs (e.g., partnership new facility in Italy where OEM Danieli provides DRI technology, while Saipem constructs the plant and integrates the technology)[1]	M
Pricing advantage potential	Given labor intensity, local variations in labor costs can provide some degree of competitive advantage. Experienced EPCs may also reduce costs by avoiding delays/budget overages	M

1. Company press releases
Source: BCG Analysis

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Clean Steel | Energy Inputs

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

Steel production requires large amounts of energy in both the furnaces for iron ore reduction (~2 tons of H2 or ~2.4 tons of NG per ton steel[1]) and in EAF for converting ore to low-carbon hot metal (~150-400 kWh/ton of liquid steel[2]). Energy must be sourced from low-carbon sources (e.g., RE, NG, GGGT+CCUS). Hot and cold steel forming also have high energy intensity (2 and 1 GJ/ton steel, respectively[3])

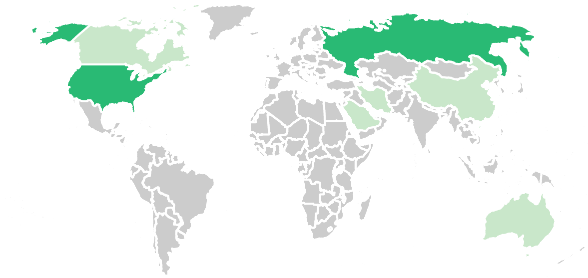
$780 - 950B

Cumulative APS U.S. SAM ($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	0	15-20	30-40	55-70
Margin[6] (%)	10-12%	10-12%	10-12%	10-12%

GLOBAL PLAYERS - COUNTRIES



🟩 > 20 EJ/year natural gas production

🟩 5-20 EJ/year natural gas production

COMPANIES

Hydrogen

VATTENFALL

Linde

AIR PRODUCTS

Natural Gas

bp

PetroChina

أرامكو السعودية saudi aramco

VALUE PROPOSITION

Access to affordable, low-carbon (H2, natural gas as stopgap, or renewable) energy sources are critical to further reduce emissions from steel production. Switching to DRI, even with NG power still results in lower emissions than traditional BF-BOF. Energy inputs can also be reduced via energy efficiency measures (e.g., heat & top gas recovery - addressed in OEM). Oppt'y exists for providers to develop competitive advantage by specializing in affordable & potentially co-locating low carbon fuels (e.g., onsite electrolysis) for clean steel production

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability and concentration	**H2-fueled DRI-EAF:** access to affordable hydrogen and/or natural gas as a stopgap. For purchasing hydrogen (vs. onsite production), development of hydrogen projects is underway, with >4 projects in China, Germany, Australia, the Netherlands, and US[4]	M
Providers/suppliers concentration	NG & energy providers are relatively fragmented and regional, which could create local competitive advantages based on local supply vs. demand. Interim natural gas production is highest in the US at ~900B m³, Russia (~700B m³) and Iran (~250B m³)[5] Hydrogen can either be produced onsite (electrolyzing at steel plant) or may be transported in, as done with NG. For purchased hydrogen, the market is fragmented, with the top 5 players controlling <40% of the market	M
Pricing advantage potential	Variations in energy costs (including local price differences) could provide some degree of competitive advantage for different H2, NG, or other low/no-carbon energy providers	L

1. Based on estimates from IEA, HYBRIT, & US Energy Information Administration 2. Estimate when using pig iron (low) or DRI (high), Air Products 3. Estimates based on figures from the Austrian Energy Agency & Freuhan et al. 2000 4. IEA Hydrogen Project Database 5. NS Energy report 6. Standard net margin for utilities, not a focus area of this study
Source: BCG Analysis

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Clean Steel | Steelmaking O&M

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

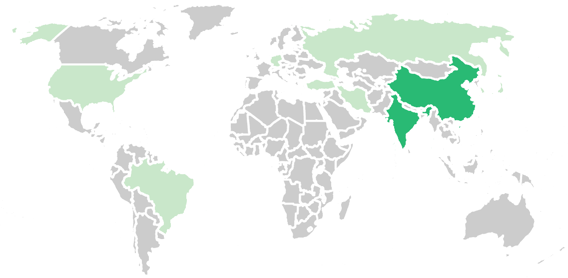
Ironmaking: processing & reducing iron ore via blast furnace (BF-BOF) or direct reduced iron furnace (DRI)
Steelmaking: converting reduced iron ore to low carbon (~95% iron & 4% carbon[1]) hot metal
Casting & forming: pouring out hot metal and using a variety of techniques (e.g., stamping, rolling, drawing, extrusion) to create steel products
Finishing & packing: Processing, cleaning, and final shaping of steel for sale; unitization & palletization

$730 - 900B
Cumulative APS U.S. SAM ($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	0	10-20	30-40	50-65
Margin (%)	8-12%	8-12%	8-12%	8-12%

GLOBAL PLAYERS - COUNTRIES



🟩 >100 Mt annual steel production
🟩 25-100 Mt annual steel production

COMPANIES

NIPPON STEEL
PRIMETALS TECHNOLOGIES
SSAB
JSW Better Everyday
voestalpine
TATA STEEL
NLMK
SALZGITTER AG Stahl und Technologie
GERDAU
USS
thyssenkrupp
BAOWU
NUCOR
SMS group

VALUE PROPOSITION

Continued cost reduction in clean steel O&M will be important as it competes with traditional methods. Deploying remote, low-cost monitoring software systems can reduce maintenance costs, limit plant downtime, and increase the quality of the product. Further, the transition to clean steelmaking techniques will require re-training of operators & maintenance technicians

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Input material availability & concentration	**DRI-EAF**: Access to affordable NG (interim) and eventually H2 (onsite electrolysis likely) CCUS	M
IP, technical expertise, and R&D availability	Potential for low-cost, remote, software-based tools to effectively monitor and provide early warnings about issues in production, especially for novel components (e.g., DRI-EAF, CCUS linkage to BF-BOF), which can be tailored for major steel producers' operations (thus more durable). TataSteel already uses predictive and remote monitoring techniques[2] through a partnership with FarEye[2]	M
Providers/supplier concentration	Existing O&M for routine cleaning and parts replacement for steel production facilities is either conducted inhouse by steel producers (e.g., Tata Steel) or outsourced to companies (e.g., to Primetals, SMS Group), with potential to specialize in newer OEM technologies for clean steel	L
Trained/skilled labor force availability	Trained labor needed for maintenance and repair of novel equipment added to existing facilities or newly created facilities with different furnaces (e.g., H_2 or NG-fueled furnaces, DRI-EAF and CCUS). Other required labor is standardized and easier to access (e.g., parts cleaning)	M
Pricing advantage potential	Low-cost remote monitoring and predictive software systems could replace manpower maintenance	M

1. Typical composition, though exact composition may vary across furnaces, BCG analysis 2. Company website
Source: BCG Analysis

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Clean Steel | Offtake

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

As with other steel, clean steel is sold to end consumers for use in construction and other large projects. Distributors tend to manage sales and transport of the final product.

$4.8 - 6.0T
Cumulative APS
U.S. SAM
($T, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	0	90-115	210-260	350-430
Margin (%)	8-12%	8-12%	8-12%	8-12%

GLOBAL PLAYERS - COUNTRIES COMPANIES

N/A

VALUE PROPOSITION

Clean steel can be sold at a 5-10+% price premium, according to a willingness-to-pay survey of customers[4], (though most steel is a global commodity with low margins & uniform prices) Strong policies/regulation are critical for growing the clean steel market opportunity, including carbon taxes and incentives for low-or-no carbon steel, protections from unfair trade, and requiring scope 3 ESG disclosures to increase demand

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. Supportiveness	Trade protections against cheap, carbon-intensive imports for high-price regions (e.g., EU & US; as in US Section 232 tariffs on imported steel, with agreements to lift tariffs on sustainable steel production[1]) Preferential market (tariff structure, direct carbon tax, or decreased fees) for low-or-no carbon metal vs. traditional (e.g., EU Carbon Border Adjustment Mechanism essentially enacting a tariff on the carbon in imported steel[2]) Policies requiring ESG disclosures (Scope 3) to incentivize clean steel use (e.g., March 2022 proposal by US SEC[3]) Procurement requirements to require certain % clean steel in end products	H
Providers/supplier concentration	While steel distribution has many national and region players, the overall market is dominated by major players	M
Market ecosystem maturity	A robust market is needed to connect clean steel providers to consumers, with information on "true" steel price (including incentives and/or import penalties for different regions)	M
Pricing advantage potential	Distributers able to sell at a lower price (e.g., due to clean steel production subsidies) will be more competitive vs. traditional steel, though consumers have indicated a willingness to pay a premium for clean steel[4]	M
Financing access	Government-funded public construction projects using only clean steel can spur steel producers to adopt cleaner production processes	M

1. European Commission press release 2. US Securities & Exchange Commission 3. US Department of Commerce and example 232 Tariff Agreement with the UK in March 2022 4. 26,573 end customers surveyed in 27 EU member states in 2012, managed by the European Commission Source: BCG Analysis

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Clean Steel | Support Services

High	Medium	Low	N/A

DESCRIPTION OF TECHNOLOGY

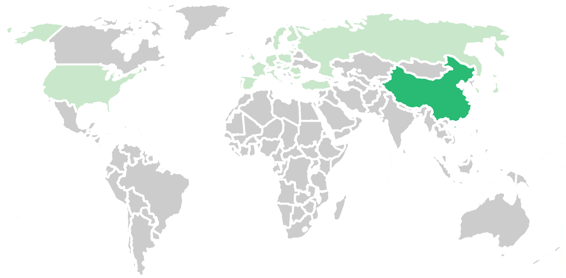
Collection and recycling of scrap metal for use in new steel products as input for scrap-EAF steelmaking

N/A
Cumulative APS U.S. SAM ($B, '20-50)

MARKET DYNAMICS

	2020	2030	2040	2050
APS U.S. SAM ($B)	N/A	N/A	N/A	N/A
Margin (%)	2-4%	2-4%	2-4%	2-4%

GLOBAL PLAYERS - COUNTRIES



🟩 > 100 Mt/year scrap used for steel production

▨ 25-100 Mt/year scrap used for steel production

*EU-28 together accounts for ~80 Mt/year

COMPANIES

OmniSource – The Best in Metals Recycling
TATA STEEL
CMC
ArcelorMittal
emr
NUCOR

VALUE PROPOSITION

Effective recycling of scrap metal can reduce costs and need of sourcing initial input materials (e.g., iron ore) and reduce processing (e.g., energy intensive ironmaking)

EVALUATION

Market	Competitive Advantage	Societal Impact

COMPETITIVE ADVANTAGES

Existing regulatory env. supportiveness	Requirements encouraging steel/scrap metal recycling over virgin steel production (e.g., European Commission's Circular Economy Package)[1]	M
Providers/supplier concentration	High access to recycling providers - many steel plants already double as recycling plants, with about 80-100 million tons of steel scrap recycled in the US annually[2] Fragmented network of steel distributors and recyclers creates high competition and drives low margins in scrap market	L

1. EU Commission 2. USGS
Source: BCG Analysis

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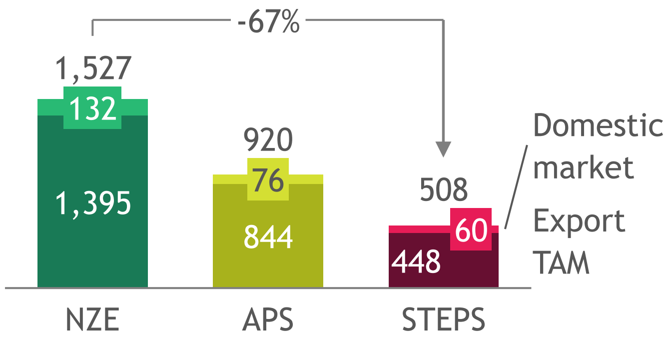
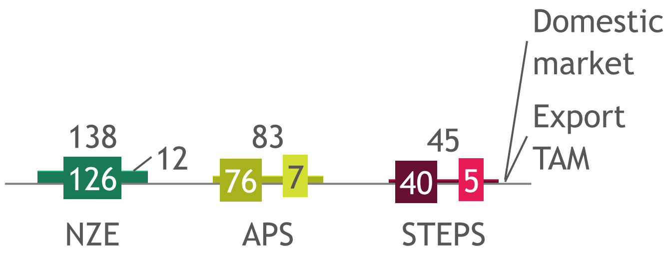
Clean Steel | OEM largest market opportunity with significant value within U.S. market, but demand-side policies will be most impactful across segments

OEM

U.S. Serviceable Addressable Market (SAM)
(2020 - 2050, $B)



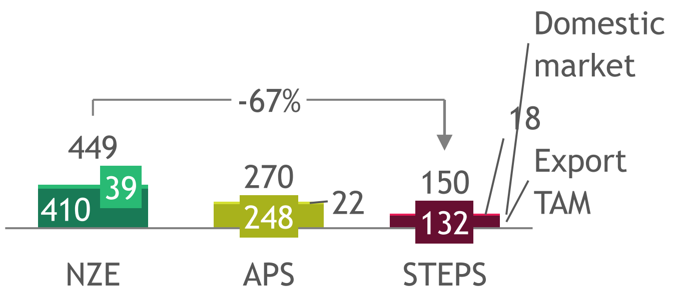
U.S. Serviceable Addressable Market Margin Pools
(2020 - 2050, $B)



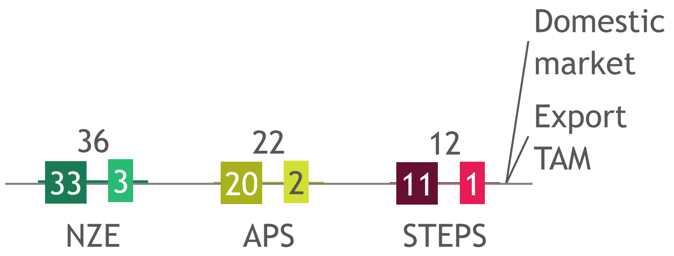
~8 - 10% Est. gross average margin

EPC

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



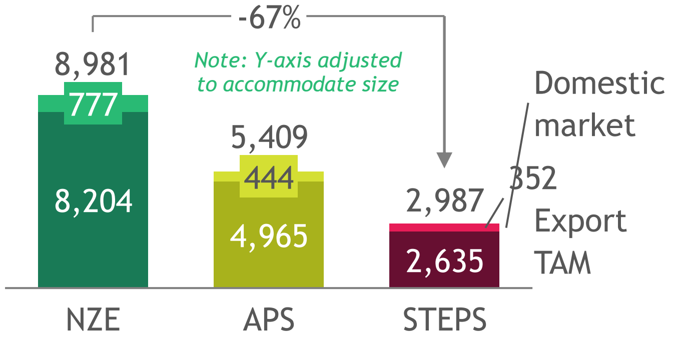
U.S. Serviceable Addressable Market Margin Pools
(2020 - 2050, $B)



~ 7 - 8% Est. gross average margin

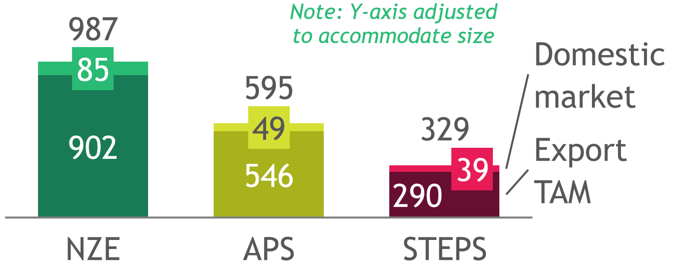
Offtake (sales)

U.S. Serviceable Addressable Market
(2020 - 2050, $B)



Note: Y-axis adjusted to accommodate size

U.S. Serviceable Addressable Market Margin Pools
(2020 - 2050, $B)



Note: Y-axis adjusted to accommodate size

~ 9 - 12% Est. gross average margin

Note: Markets do not include "green premium" in sizing
Source: BCG analysis

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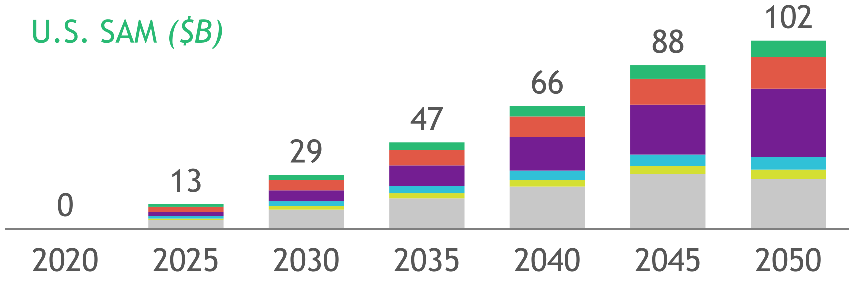
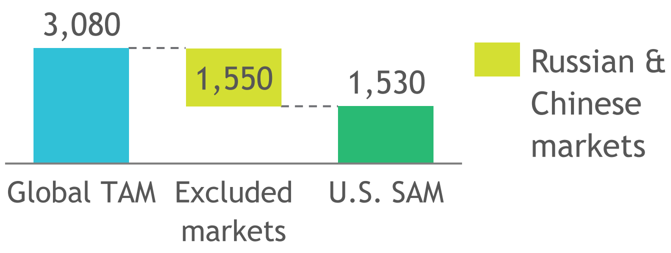
OEM | 3X delta between SAM in STEPS vs. NZE, with India has major value center in NZE as the world's most rapidly growing steelmaking nation

Net Zero Emissions Scenario

$1.5T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

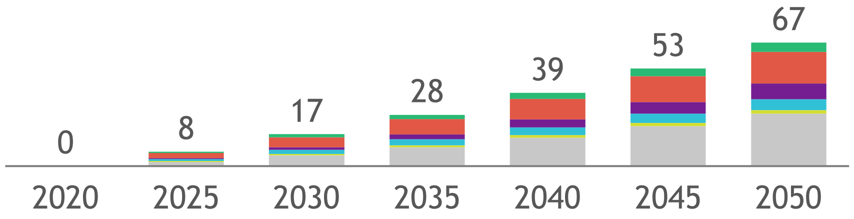

U.S. SAM *($B)*

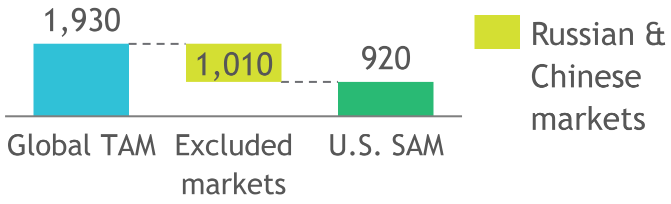

Cumulative Global Market *(2020-2050, $B)*

Announced Pledges Scenario

$920B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

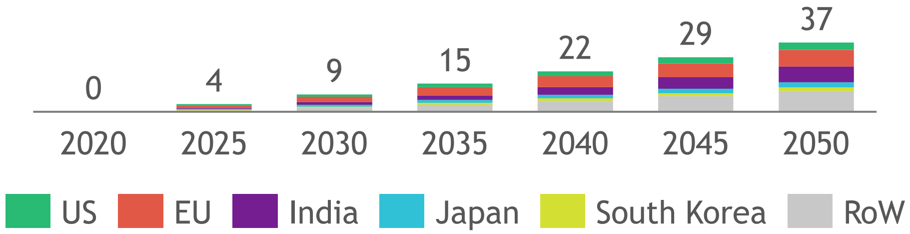

U.S. SAM *($B)*

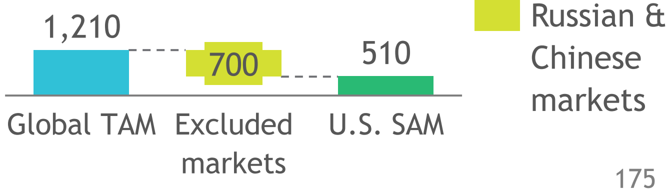

Cumulative Global Market *(2020-2050, $B)*

Stated Policies Scenario

$500B

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*


U.S. SAM *($B)*


Cumulative Global Market *(2020-2050, $B)*

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[1] Includes both U.S. domestic market and total export SAM

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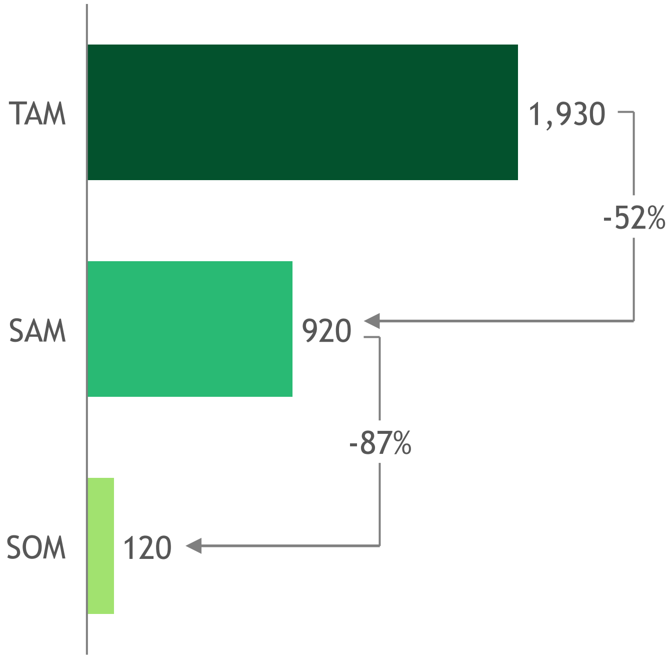
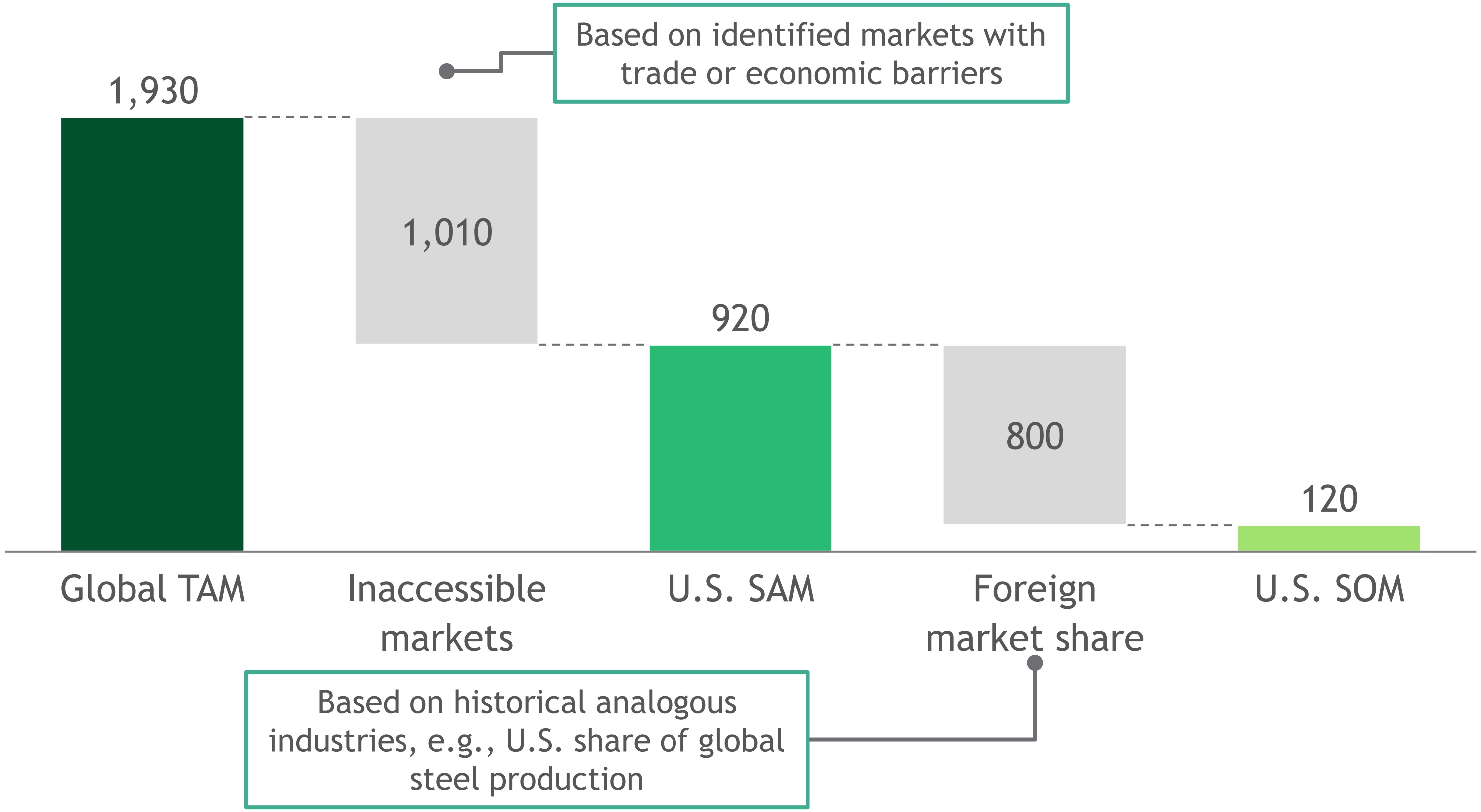
OEM | Large 16X delta between TAM and SOM driven by small US share of global steel production today, major international OEMs with large presence

APS market sizing metrics

Cumulative market value, 2020 – 2050 *($B)*



Walk from TAM to SOM under APS scenario



Based on identified markets with trade or economic barriers

Based on historical analogous industries, e.g., U.S. share of global steel production

Source: World Steel Association, IEA, BCG analysis

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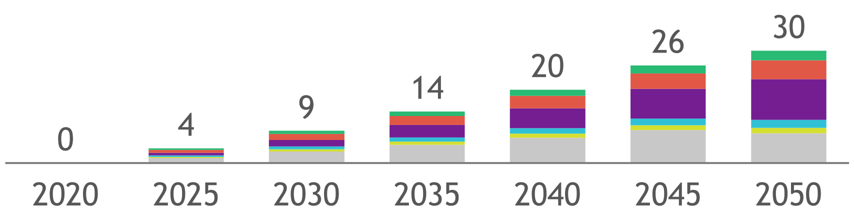
EPC | Much EPC value will be captured by local markets, but opportunity to target developing countries including India with EPC support services

Net Zero Emissions Scenario

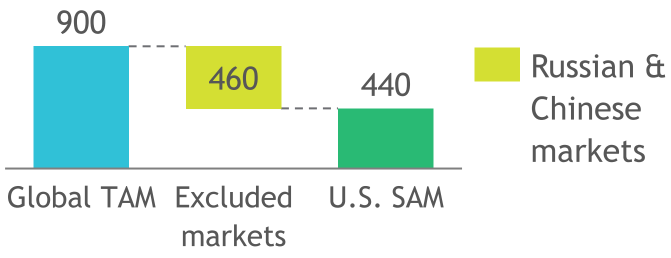
$440T

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

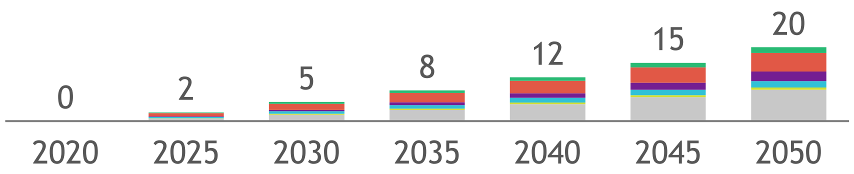


Announced Pledges Scenario

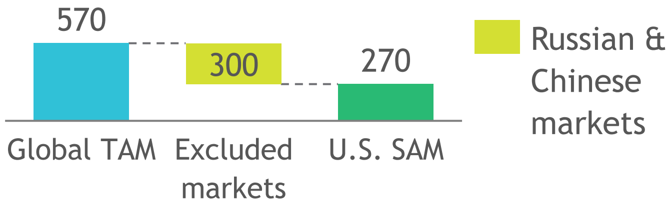
$270B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

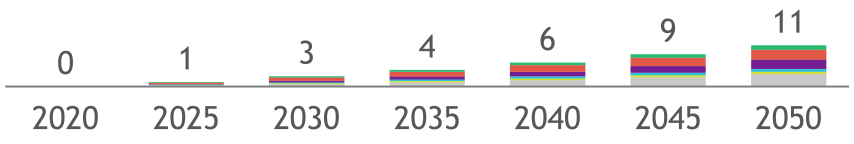


Stated Policies Scenario

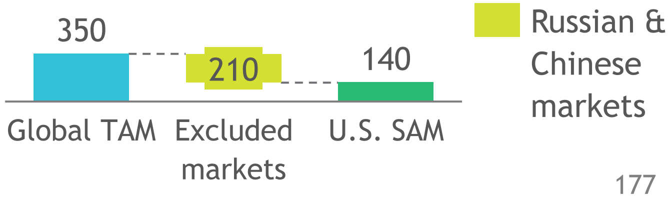
$140B

Cumulative U.S. Serviceable Addressable Market[1]
(2020 - 2050)

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*



🟩 US 🟥 EU 🟪 India 🟦 Japan 🟨 South Korea ⬜ RoW

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[1] Includes both U.S. domestic market and total export SAM

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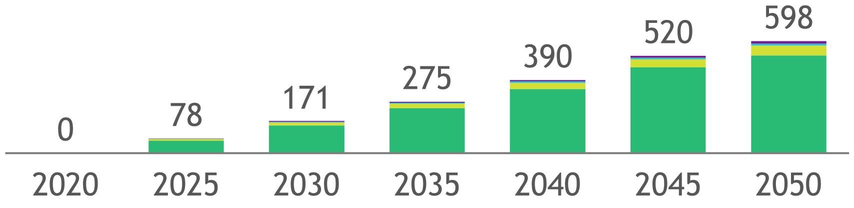
Offtake | Large addressable global market, but obtainable Mexico, Canada represent small portion, totaling only ~$25B in 2050

Net Zero Emissions Scenario

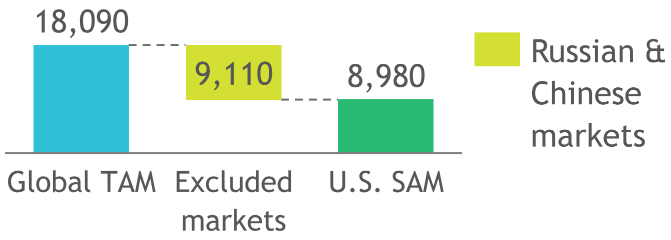
$9T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

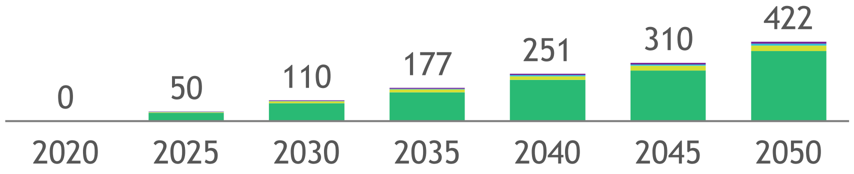


Announced Pledges Scenario

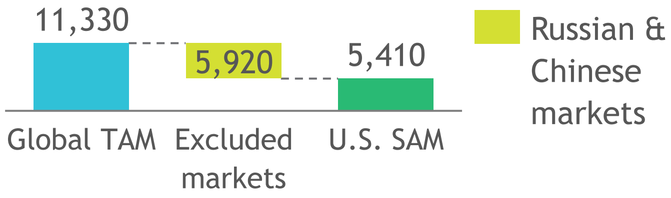
$5.4T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*

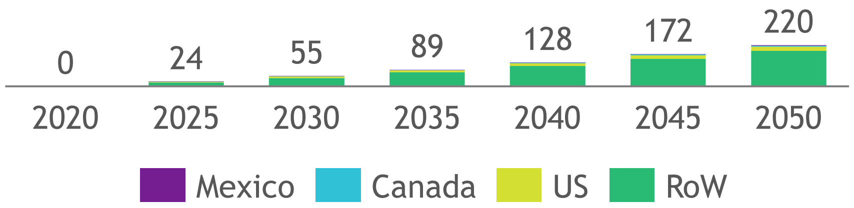


Stated Policies Scenario

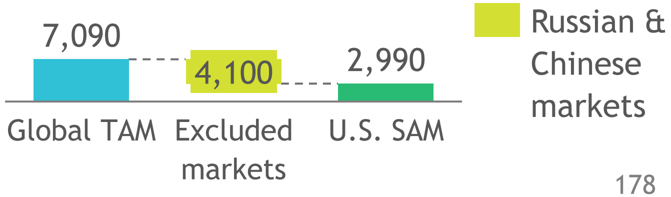
$3T

Cumulative U.S. Serviceable Addressable Market[1] *(2020 - 2050)*

U.S. SAM *($B)*



Cumulative Global Market *(2020-2050, $B)*



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1. Includes both U.S. domestic market and total export SAM

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OEM | U.S. behind in equipment OEM, with China leading in patent & research activity and few mature dedicated manufacturers or suppliers today

☆ = *Key dimension*

	Areas for Competitive Advantage	Ranking	Summary analysis
	Raw material availability	N/A	• Not applicable in segment
☆	**Intellectual Property & innovation**	Low	• US is 3rd globally in OEM-relevant clean steel patent volume, behind China and Germany • China a clear 1st across most major segments, including EAF, DRI and CCUS technology-related patents • US has small lead in emerging molten oxide electrolysis segment, but low total activity
	Research & technical leadership	Low	• China the publication leader across all equipment technologies, including DRI, EAF, CCUS, and molten oxide electrolysis, surpassing US in overall impact in most segments • China the leader in overall CCUS literature volume, but U.S. is a close second and first in sequestration research. Domestic CCUS researchers also have greater impact, with more total citations than those from other nations
	Low operational costs	Low	• U.S. labor costs are high compared to many major steelmaking regions such as East & South Asia as well as parts of Europe, but labor and energy costs are relatively limited drivers of OEM cost & competitiveness
☆	**Demand / supply side policy**	Low	• The U.S. has no dedicated clean steel policies. Minor private-sector initiatives, such as the First Movers Coalition, are helping generate small-scale demand, but domestic policy is behind competing nations • Europe is moving to implement a strong carbon border-adjustment mechanism (CBAM) that will incentivize the growth of the regional clean steel market & industry, and likely spur demand for the major OEMs, particularly within Europe • Domestically, 45Q is a potential driver of CCUS projects, but no CCUS-steel facilities are active today
☆	**Relative domestic market maturity**	Low	• U.S. has notable presence in clean-steel related investment activity, particularly around emissions reduction and carbon capture technologies, but few leading players. Domestic OEM is nascent, and most steelmakers do bulk of OEM in-house, acting as sole designer, procurer, and general contractor, with minimal turnkey solutions available for export • Notably, however, most East Asian (particularly Chinese) investments are in large part driven by public initiatives, internal corporate investments, or state-owned corporations, and are not visible in this private investment market assessment • The high patent activity of Chinese, Japanese, and Korean steelmakers suggest major investment is occurring in those markets • U.S. also has strong presence in CCUS space with leading amount of deployed capacity today, but no active steel-CCUS sites • Notably, Canadian steelmakers have made a commitment to be net-zero by 2050, opening a potential opportunity to deploy US-based EAF, DRI, and CCUS experience to Canadian partners, but may be hindered by competition
	Regulatory environment & existing infrastructure	Low	• U.S. has strong regulatory and political ecosystem for steelmakers that provides sufficient capital, permitting, and labor support, but minimal opportunity for impact in clean steel sector aside from direct demand-side subsidies
	Overall ranking	🟨	The limited number of dedicated U.S. OEMs today, coupled with a gap to the leader in innovation and research across clean steelmaking equipment technologies, suggests the US has relatively low competitive advantage in the segment today

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EPC | EPC largely driven by OEMs, and similarly impacted by small U.S. presence. Some opt'y to leverage comparatively stronger position in CCUS

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	- Not applicable in segment
Intellectual Property & innovation	N/A	- Not applicable in segment
Research & technical leadership	N/A	- Not applicable in segment
Low operational costs	Low	- U.S. labor costs are high compared to many major steelmaking regions such as East & South Asia, parts of Europe, and areas of the Middle East where CCUS technology has found early traction
☆ **Demand / supply side policy**	Low	- The U.S. has no dedicated public clean steel policies. Minor movement around private-sector initiatives, such as the First Movers Coalition, are helping generate small-scale demand, but domestic policy is behind competing nations in direct support - Europe is moving to implement a strong carbon border-adjustment mechanism (CBAM) that will incentivize the growth of the regional clean steel market & industry
Relative domestic market maturity	Low	- Significant U.S. investment activity in incorporating emissions reduction/efficiency improvements across existing technologies, with small amounts of CCUS EPC activity occurring in U.S. - Canada seeing significant CCUS EPC activity in part due to large-scale plants across other industries today. Additionally, potential opportunity created by the Canadian Steel Producers Association's (CSPA) Net Zero by 2050 commitment - Most U.S. steelmakers perform in-house EPC, limiting the opportunity for separate , dedicated EPC providers - Most investments in the space are internal investments made by existing market players, so are not captured in this analysis and likely underrepresent the relative position of U.S. steelmakers
Regulatory environment & existing infrastructure	Low	- U.S. has strong regulatory and political ecosystem for steelmakers that provides sufficient capital, permitting, and labor support, but minimal opportunity for impact in clean steel sector aside from direct demand-side subsidies
Overall ranking		Given EPC is so closely integrated with OEMs, U.S. has similarly low competitive advantage in the space today. Many domestic steelmakers has strong & experienced EPC teams dealing with EAF and DRI technologies, but limited standalone activity and a resistance to servicing other steelmakers reduces both the domestic growth opportunity & export potential

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Offtake| U.S. production well-positioned given low carbon intensity, but behind on policy, financial support for generating clean steel demand

☆ = *Key dimension*

Areas for Competitive Advantage	Ranking	Summary analysis
Raw material availability	N/A	- Not applicable in segment
Intellectual Property & innovation	N/A	- Not applicable in segment
Research & technical leadership	N/A	- Not applicable in segment
Low operational costs	Low	- U.S. has higher labor costs given high average operator salaries, but any cost disadvantages are largely offset by the lower costs of energy, which are a major proportion of EAF steelmaking operating expenses. US maintains competitiveness in overall delivered cost within North America, given transportation economics, but is sensitive to fluctuating costs/outputs of foreign producers and changes in tariffs or anti-dumping regulations - Overall costs are often comparable to European producers, which are subject to strict labor & environmental regulations and older mills, but higher than Asian producers, reflected by the higher average North American steel price/ton vs. average international markets historically - Additionally, the historical low cost of domestic natural gas has driven investments in domestic DRI production facilities
☆ **Demand / supply side policy**	Low	- The U.S. has no dedicated, broad-based public clean steel policies. Minor movement around private-sector initiatives, such as the First Movers Coalition, and small public programs such as the Buy Clean Task Force and DoE grants, are helping generate small-scale demand, but domestic policy is behind competing nations in direct support - Europe is moving to implement a strong carbon border-adjustment mechanism (CBAM) that will incentivize the growth of the regional clean steel market & industry
Relative domestic market maturity	N/A	- Not applicable in segment
☆ **Regulatory environment & existing infrastructure**	High	- U.S. is the major source of steel for North America and its production base is well-positioned for the clean steel transition. Given the high existing proportion of scrap-based EAF production, the U.S. is one of the lowest carbon-intensity producers globally today. Domestic producers could benefit from U.S. and international carbon border adjustment mechanisms and other emissions-related subsidies/incentives, as other steel producers must invest significant capital to come into emissions parity with U.S. minimills
Overall ranking		With demand-side policy being by far the strongest driver of clean steel market demand, the U.S. is behind other nations with no incentives for clean steelmaking, but this can be rapidly shifted with changes in incentives & policy

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Clean steel | Key assumptions and sources for modeling

Assumptions	Value	Impact on modeling	Source
Regional steel production volumes, 2020-2050	Variable	Any shifts in steel demand that are not modeled, included broad macro-economic trends or changes in steel consumption habits/consumption reduction measures, may impact overall steel demand and thus clean steel proportionally	World Steel Association growth projections, BCG analysis
Steel price/ton, hot-rolled coil (HRC) as proxy for industry	NA: $705/ton RoW: $550/ton	HRC prices, used as proxy for the broader steel industry, directly drive steel offtake projections, and indirectly impact capital expenditure modeling by reducing overall market size	World Steel Association Steel Statistical Yearbooks
Proportion of steel production that is clean, global NZE scenario, 2050	95% (in 2050, variable)	% assumptions in each scenario drive overall market size by multiplying against global steel demand projections	IEA Iron & Steel Technology Roadmap, 2020
Proportion of steel production that is clean, global APS scenario, 2050	59% (in 2050, variable)	% assumptions in each scenario drive overall market size by multiplying against global steel demand projections	IEA Iron & Steel Technology Roadmap , 2020
Proportion of steel production that is clean, global STEPS scenario, 2050	37% (in 2050, variable)	% assumptions in each scenario drive overall market size by multiplying against global steel demand projections	IEA Iron & Steel Technology Roadmap , 2020

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