Goldman Sachs 高盛

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Global Automation

Humanoid Robot: The AI accelerant

A year after we laid our initial expectations for global humanoid robot TAM of US$6bn, we raise our 2035 TAM forecast to US$38bn resulting from a 4-fold increase in our shipments estimate to 1.4mn units with a much faster path to profitability on a 40% reduction in bill of materials. We believe our revised shipment estimate would cover 10%-15% of hazardous, dangerous and auto manufacturing roles. AI acceleration, technology breakthroughs, greater capex investments are the key drivers of our forecast changes.

- Improved **technological viability** is supported by incorporation of end-to-end AI and multi-modal AI algorithms enabling much faster product iterations, leading players' sooner-than-expected progress (e.g., Tesla Optimus Gen 2), and better capabilities of the robots though possibility for a general purpose AI robot is still a question;
- **BOM cost trended down likely by 40% to $150k per unit in 2023 from c. $250k a year ago** for high spec robots mainly driven by availability of cheaper components with broader scope of domestic supply chain options from the best performance components used in labs previously, implying a likely acceleration in factory application viability timeline by one year and consumer applications timeline by 2-4 years vs our prior estimates;
- On **labor market implications**, the need for robots to handle dangerous jobs is already elevated by national policy. Our sensitivity analysis suggests humanoid robot demand could reach 1.1mn-3.5mn units globally assuming 5-15% substitution rate for special operations and auto manufacturing to support our base case assumptions. In our blue-sky scenario, we assume manufacturing labor shortage and household/elderly care demand to be addressed.

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What is special in this report

Differentiated view vs. market expectations:

Our shipment estimates until 2025E are likely in line or slightly lower than various company comments, but long run outlook looks highly debatable with 1mn units a commonly discussed investor expectation but with varied timeline and highly polarized market views with the most aggressive expectation of as high as 200mn units eventually and the most bearish view that humanoid robot will never work. Below are the key factors we consider in our base case:

- **The AI progress surprised us the most**: We view hardware technology is mostly ready while progress in **end-to-end AI (completely different from rule-based control) could potentially enable much faster humanoid robot iterations** as seen from the improvement of manipulation and interaction capabilities of various products in 2023 (for e.g., Tesla Optimus Gen 2).
- **The cost curve: BOM cost trended down likely by 40% to $150k per unit in 2023 from c.$250k a year ago** for high spec robots mainly driven by availability of cheaper components with broader scope of supply chain options from the best performance components in labs previously, **thus far driving better application economics**, which means **factory application viability timeline could be one year earlier (2024E-27E vs. 2025E-28E previously) and consumer applications 2-4 years earlier (2028E-2031E vs. 2030E-2035E).**
- **The potential demand:** Considering current technological capabilities, we view humanoid robot has visible demand from jobs in **structured environment such as manufacturing** (e.g. EV assembly and component sorting). Given its likely adaptability to dynamic environment enabled by AI algorithms, we believe humanoids look particularly appealing for **special operations such as dangerous and hazardous tasks**, considering the associated fatality rate and people's low willingness in doing such jobs thus customers' likely willingness to pay a higher price than typical manufacturing work.
- **Growing investments**: We are seeing stronger commitment from the supply chain, start-ups in the US and Asia, multiple listed players setting up new robot divisions and potentially more government support (i.e. from China).

Changes in our investment case:

- **For our base case**, we raise up our humanoid robot shipment forecast by **75%-389% across 2024-2035E** as 1) we see accelerated advancement in AI, better hardware configuration, widened & deepened manufacturing supply chain especially in China, significant cost reduction, and improving visibility on special operations and manufacturing application settings; 2) we take into account not only the high-spec robots, but also the low & mid-spec robots after MIIT elevated the strategic importance of humanoid robot industry development;
- **For our bear case**, our previous bear case assumption of a potential market exit by 2028E looks unlikely now given technology advancement; we now expect a delay in

high-spec humanoid robots' volume production **by two years vs. our base case could be possible due to technology bottlenecks or manufacturing constraints.**

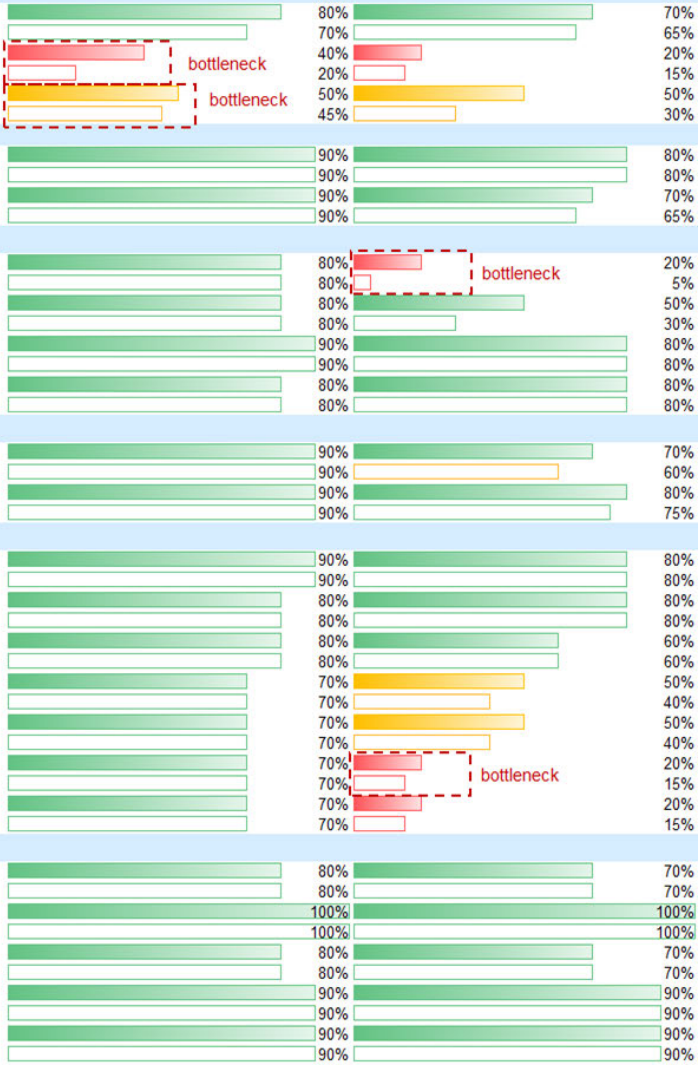
- **For our bull case**, we expect humanoid robot shipment to **hit 1mn units by 2031E** (four years ahead of our previous expectation of 2035E), accelerated by advancement in end-to-end AI; **For our blue-sky scenario**, we still expect humanoid robot to become the next commonly adopted technology after EVs and smartphones, and we turn more positive on the potential of humanoid robot to tap into more consumer applications and expect the adoption to be **faster by a year compared to our previous forecasts**.

Key thesis in charts

Exhibit 1: We believe hardware are mostly ready and progress in end-to-end AI could potentially enable much faster humanoid robot iteration as seen from the improvement of manipulation and interaction capabilities in 2023

Our evaluation of humanoid robot technology readiness

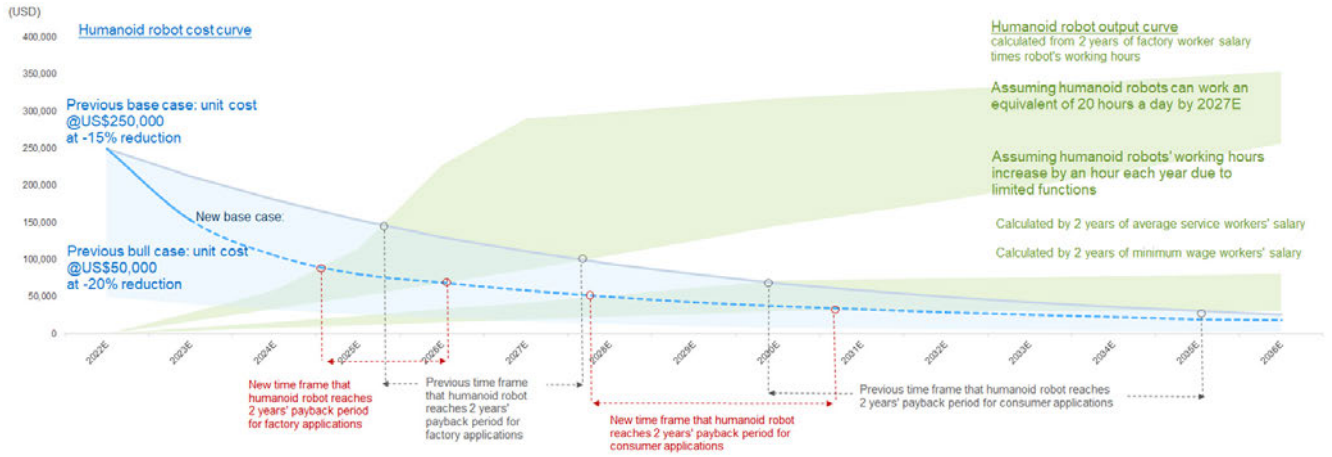
Components	% of hardware BOM in high-spec robot in2024E	Application	CHN name	Time	Global top players' technology readiness	Domestic top players' technology readiness
AI/Software			**软件**			
Navigation		-	导航	2023	80%	70%
				2022	70%	65%
Manipulation		-	操纵	2023	40%	20%
				2022	20%	15%
Interaction		-	交互	2023	50%	50%
				2022	45%	30%
Motors						
Frameless torque motor	4%	Linear & Rotary	无框力矩电机	2023	90%	80%
				2022	90%	80%
Coreless motor	6%	Hand	空心杯电机	2023	90%	70%
				2022	90%	65%
Transmission			**直线执行器**			
Planetary roller screw	31%	Linear	行星滚柱丝杠	2023	80%	20%
				2022	80%	5%
Trapezoidal screw	2%	Linear	梯形丝杠	2023	80%	50%
				2022	80%	30%
Harmonic reduction gear	4%	Rotary	谐波减速器	2023	90%	80%
				2022	90%	80%
Planetary reduction gear	<1%	Hand & Rotary	行星减速器	2023	80%	80%
				2022	80%	80%
Chips			**芯片**			
Main chip	<1%	-	主芯片	2023	90%	70%
				2022	90%	60%
MCU chip	1%	-	MCU芯片	2023	90%	80%
				2022	90%	75%
Sensors			**传感器**			
Camera	<1%	-	摄像头	2023	90%	80%
				2022	90%	80%
Position sensor	2%	Body	位置传感器	2023	80%	80%
				2022	80%	80%
Inertial Measurement Unit	<1%	Body	惯性导航	2023	80%	60%
				2022	80%	60%
Force sensor	1%	Linear	力传感器	2023	70%	50%
				2022	70%	40%
Torque sensor	1%	Rotary	扭矩传感器	2023	70%	50%
				2022	70%	40%
6D torque sensor	10%	Hand	六维力矩传感器	2023	70%	20%
				2022	70%	15%
Tactile sensor	<1%	Hand	触觉传感器	2023	70%	20%
				2022	70%	15%
Others			**其他**			
Battery (kWh)	<1%	-	电池 (kWh)	2023	80%	70%
				2022	80%	70%
Wireless	1%	-	通讯	2023	100%	100%
				2022	100%	100%
Cooling	1%	-	散热	2023	80%	70%
				2022	80%	70%
Drive	2%	-	驱动器	2023	90%	90%
				2022	90%	90%
Encoder	2%	-	编码器	2023	90%	90%
				2022	90%	90%



Note: Different colors represent the degree of technology readiness, with more ready, needing upgrade, less ready corresponding to green, yellow, and red. Bottlenecks are components that have a relatively significant proportion in BOM with low technology readiness for robot mass production.

Source: Company data, compiled by Goldman Sachs Global Investment Research

Exhibit 2: Meanwhile, cost reduction also trended much faster than our prior expectation, implying factory application viability timeline could be one year earlier (2024E-27E vs. 2025E-28E previously) and consumer applications 2-4 years earlier (2028E-2031E vs. 2030E-2035E)
Humanoid robot payback period analysis (new vs. prior expectations)



Note: Blue shaded area represents the possible range of humanoid robot ASP cost reduction and the green shaded area represents the possible range of humanoid robot productivity output assuming the robot's efficiency is twice a human worker; the crossing points represent the payback point for humanoid robot.

Source: Goldman Sachs Global Investment Research

Exhibit 3: We thus raise our 2024-2035E global humanoid robot shipment forecasts
Global humanoid robot shipment forecasts (new vs. prior)

Rationale for forecast change	
Base case	We reivse up our humanoid robot shipment forecast by 75%-389% across 2024-2035E as 1) we see accelerated advancement in AI, better hardware configuration, widened & deepened manufacturing supply chain especially in China, significant cost reduction, and improving visibility on manufacturing application settings; 2) we take into account not only the high-spec robots, but also the low & mid-spec robots after MIIT elevated the strategic importance of humanoid robot industry development;
Bear case	We expect low/mid-spec humanoid robots to be introduced in the market first without much real demand support, while high-spec humanoid robots' volume production to be delayed by two years vs. our base case due to technology bottlenecks or manufacturing constraints. (Our previous bear case of potential market exit by 2028E looks unlikely now).
Bull case	We expect humanoid robot shipment to hit 1mn units by 2031E (four years ahead of our previous expectation of 2035E), accelerated by advancement in end-to-end AI.
Blue-sky scenario	We expect humanoid robot to become the next commonly adopted technology after EVs and smartphones, as a "must-have" electronics device. We turn more positive on the potential of humanoid robot to tap into more consumer applications and expect the adoption to be faster by a year compared to previous forecasts.

Global shipment (k units) - new	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E	2031E	2032E	2033E	2034E	2035E	2025-35E CAGR
Base case	1.0	3.5	20	51	76	114	171	256	359	502	703	985	1,378	53%
Industrial	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*95%*	*84%*	*69%*	*56%*	*46%*	*38%*	
Consumer	-	-	-	-	-	-	-	*5%*	*16%*	*31%*	*44%*	*54%*	*62%*	
Bear case	1.0	1.0	1	4	20	51	76	114	171	256	359	502	703	n.m.
Industrial	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*95%*	*84%*	*69%*	*56%*	
Consumer	-	-	-	-	-	-	-	-	-	*5%*	*16%*	*31%*	*44%*	
Bull case	1.0	6.8	30	75	148	299	594	890	1,323	1,966	2,924	4,351	6,478	71%
Industrial	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*63%*	*53%*	*44%*	*37%*	*31%*	*26%*	*22%*	
Consumer	-	-	-	-	-	*5%*	*37%*	*47%*	*56%*	*63%*	*69%*	*74%*	*78%*	
Blue-sky scenario	1.0	10	40	100	220	484	1,016	1,525	2,287	3,430	5,146	7,718	11,577	76%
Industrial	*100%*	*100%*	*100%*	*100%*	*95%*	*62%*	*38%*	*33%*	*29%*	*25%*	*22%*	*19%*	*16%*	
Consumer	-	-	-	-	*5%*	*38%*	*62%*	*67%*	*71%*	*75%*	*78%*	*81%*	*84%*	

Global shipment (k units) - old	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E	2031E	2032E	2033E	2034E	2035E	2025-35E CAGR
Base case	1.0	2.0	10	15	23	34	51	76	99	128	167	217	282	40%
Bear case	1.0	2.0	10	8	4	2	-	-	-	-	-	-	-	n.m.
Bull case	1.0	2.0	10	20	37	61	92	137	206	309	464	695	1,043	59%
Blue-sky scenario	1.0	2.0	10	40	100	220	484	1,016	1,525	2,287	3,430	5,146	7,718	94%

Global installbase (k units) - new	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E	2031E	2032E	2033E	2034E	2035E	2025-35E CAGR
Base case	1.0	4.5	25	75	151	264	430	662	946	1,297	1,736	2,291	3,007	62%
Bear case	1.0	2.0	3	7	27	76	150	261	425	655	938	1,290	1,732	n.m.
Bull case	1.0	7.8	38	113	261	559	1,145	1,997	3,207	4,913	7,279	10,486	14,966	82%
Blue-sky scenario	1.0	11.0	51	151	371	854	1,859	3,333	5,469	8,528	12,820	18,679	26,923	87%

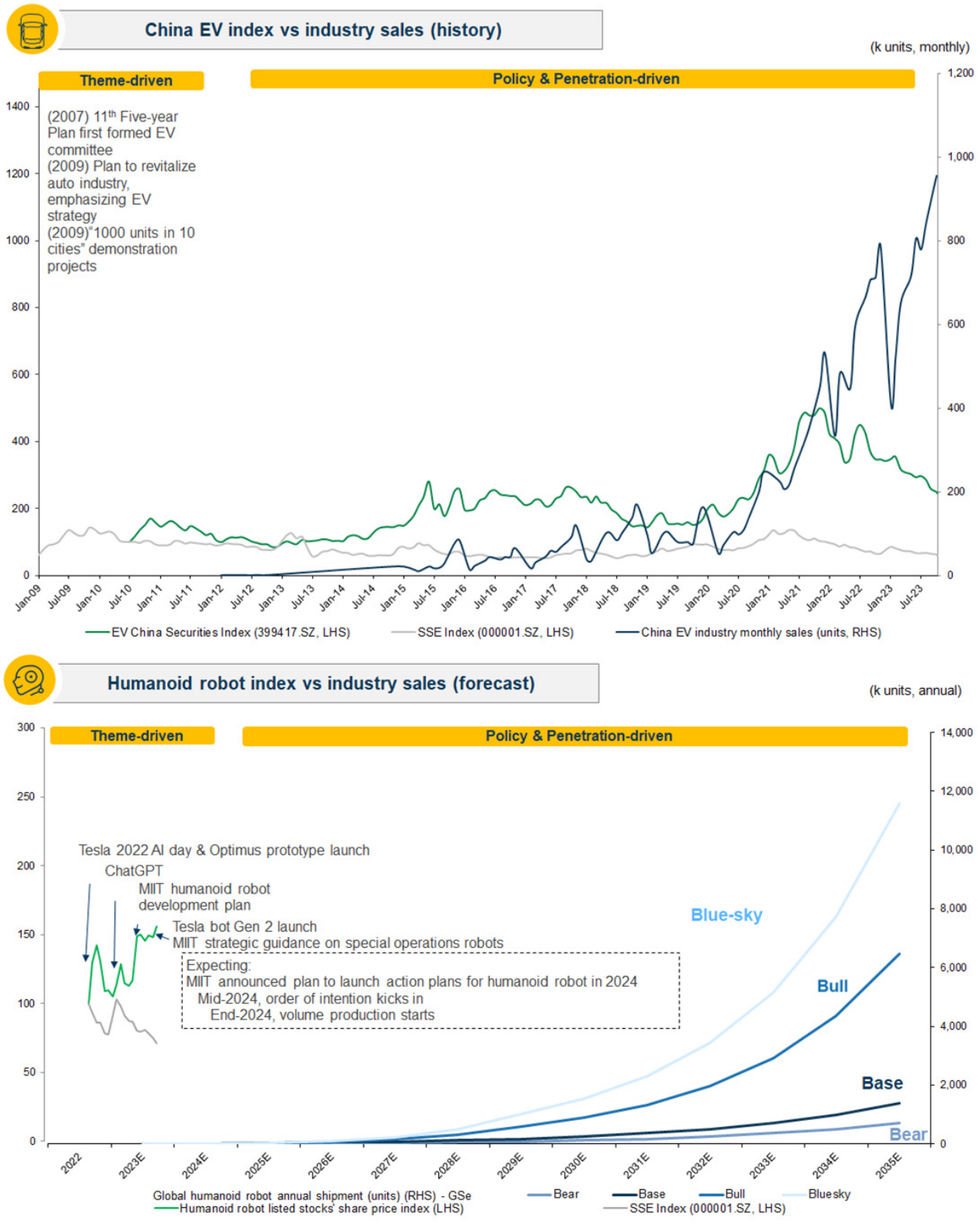
Global installbase (k units) - old	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E	2031E	2032E	2033E	2034E	2035E	2025-35E CAGR
Base case	1.0	3.0	13	28	51	83	131	194	265	342	426	512	600	47%
Bear case	1.0	3.0	13	21	25	26	23	10	-	-	-	-	-	n.m.
Bull case	1.0	3.0	13	33	70	130	219	343	516	755	1,089	1,565	2,266	68%
Blue-sky scenario	1.0	3.0	13	53	153	372	853	1,856	3,328	5,462	8,520	12,813	18,675	107%

Note: We assume a 5-year life cycle in our installbase forecasts.

Source: Goldman Sachs Global Investment Research

Exhibit 5: Humanoid robot stocks have been theme-driven since mid-2022 while in our view concrete shipment volumes could emerge more materially heading into 2024E onwards

Comparison of humanoid robot stocks performance since mid-2022 vs. EV index in history (2009-2023)



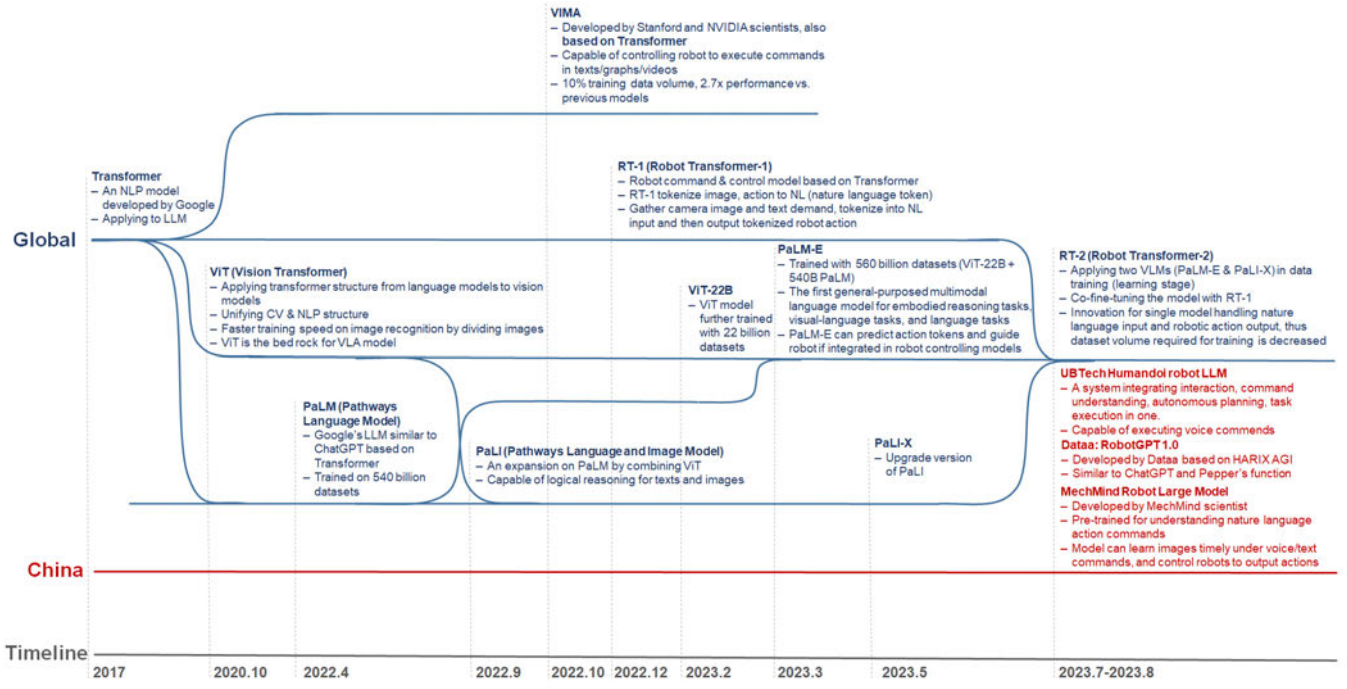
Note: EV China Securities Index is 399417.SZ. Humanoid robot index is constructed by us using Sanhua, LeaderDrive, Moons' Electric, BEST precision, Tuopu, using market-cap weighted method. EV China Securities Index (in July 2010), SSE Index (in July 2010), and humanoid robot index (in June 2022) are rebased to 100.

Source: Wind, MIIT, Goldman Sachs Global Investment Research

The AI progress surprised us the most

Robotic LLMs development surprised us the most in 2023, such as the launch of PaIM-E and RT-2, as well as Tesla's end-to-end AI approach to develop humanoids. The bedrock for all robot LLMs today is Google's Transformer model, which was developed since 2017, introducing a novel neural network architecture based on a self-attention mechanism. Based on the Transformer model structure, Google continued to develop three types of models: **1) PaLM (Pathways Language Model)**, focusing on text content analysis and generation; **2) ViT (Vision Transformer) & PaLI (Pathways Language and Image Model)**, combining texts and images analysis, transforming and reasoning; **3) RT (Robot Transformer)**, using tokenized input and output to connect input commands and robot output control. The three types of models evolved through their technology paths into PaLM-E, PaLI-X and RT-1, and by applying PaLM-E & PaLI-X in data training and RT-1 in fine-tuning, Google introduced RT-2 in July 2023. RT-2 is capable of processing natural language commands and analyzing tasks' scenarios through vision thanks to PaLM-E and PaLI-X's multimodal analysis capabilities, and is able to control robots to execute tasks thanks to RT-1's movement database and tokenized data processing technology. RT-2's end-to-end AI capability is based on a robot movement database, taking Google 1.5 years to collect the data, thus RT models have longer R&D period vs. the other two types. After RT-2's release, select China robotic companies also launched their own robot LLMs, while in our view the AI capabilities of most domestic humanoid robot OEMs at the moment are developed based on open-sourced robot LLMs (large language models), such as from OpenAI, Meta and Google Deepmind.

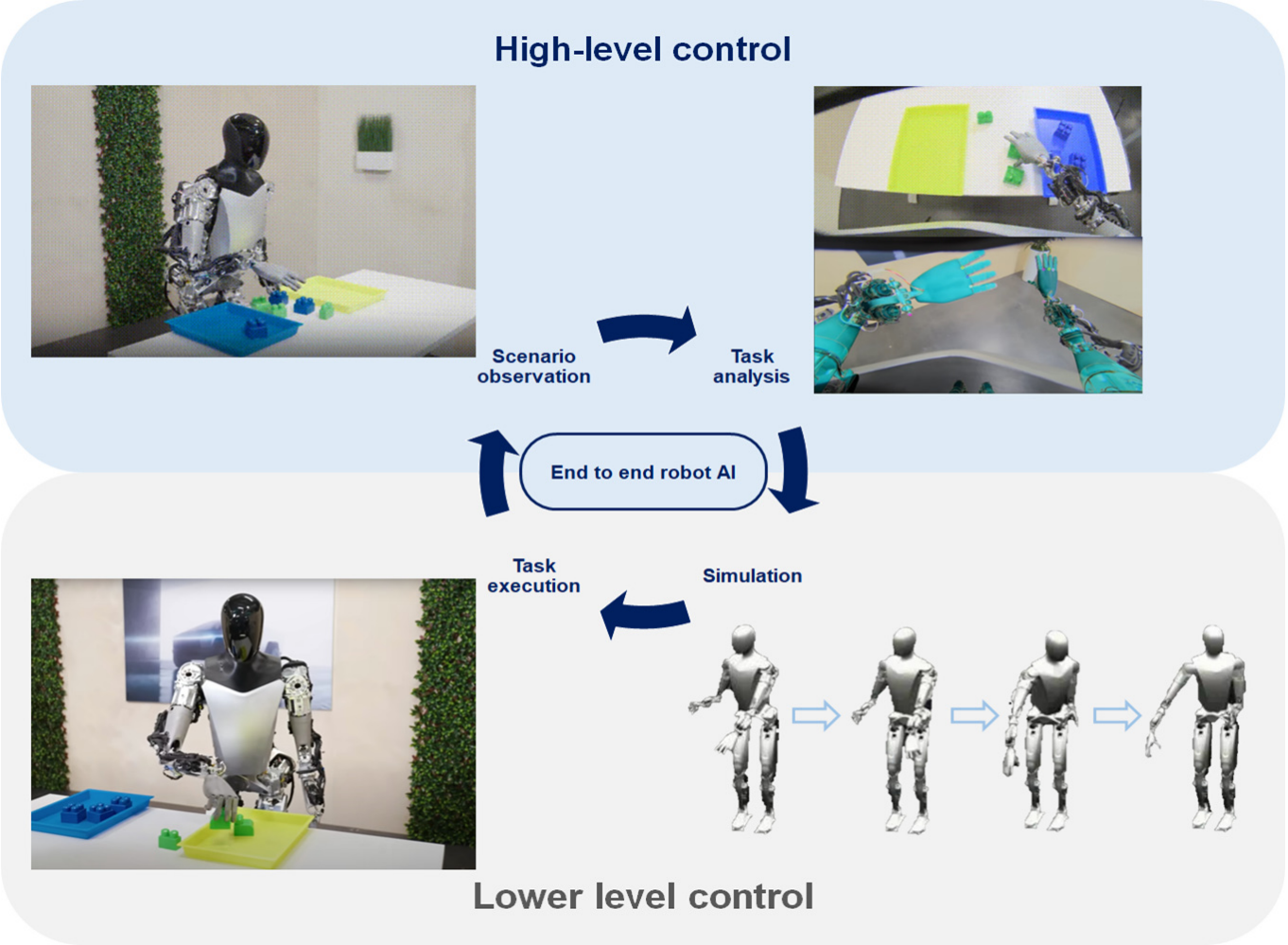
Exhibit 9: Robotic LLMs development surprised us the most in 2023, such as the launch of PaIM-E and RT-2
Key robotics LLMs development timeline



Source: Data compiled by Goldman Sachs Global Investment Research, Ubtech, Mechmind, Dataa, Google, Nvidia

Tesla released a video in Sep 2023 to elaborate their end-to-end AI process in Optimus. End-to-end AI is completely different from prior rule-based control, meaning the software system itself can execute the task from original commands and scenarios to final outputs under AI self-generated rules instead of software engineers' pre-programmed rules. In the video, Tesla Optimus completed the **higher-level end-to-end control** from scenario observation to task analysis. These two processes are completed by robot LLMs as they have image/text/video reasoning and analysis abilities. The **lower-level end-to-end control** includes simulation and final execution, where robot AI needs to arrange the workflow of movements (simulation) and then turn into the robot physical movements that we see.

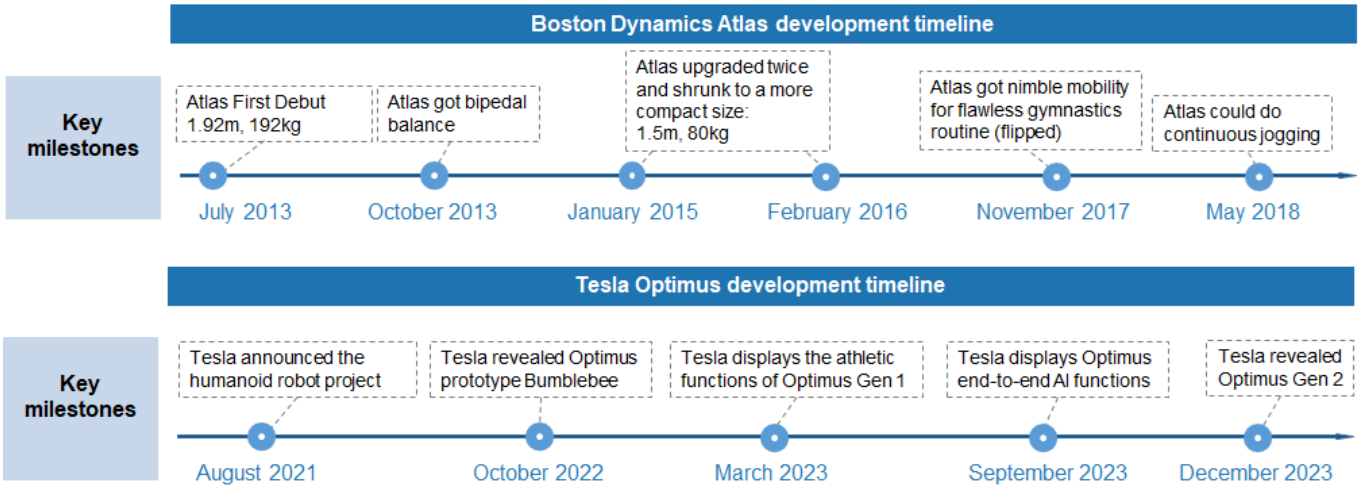
Exhibit 10: End-to-end AI is completely different from prior rule-based robot control
Illustration of end-to-end robot AI



Source: Company data, Data compiled by Goldman Sachs Global Investment Research

On Dec 13, 2023, Tesla unveiled Tesla Optimus Bot Gen 2 in video format. We note Tesla launched its Gen 1 product nine months back in March 2023 and three months after they demonstrated the end-to-end AI learning capabilities, showing a much faster product iteration and R&D pace than comparable peers.

Exhibit 11: ...which enabled much faster robot iteration pace that we saw in 2023
Tesla Bot development timeline vs Boston Dynamics Atlas



Source: Company data, compiled by Goldman Sachs Global Investment Research

Exhibit 12: We believe hardware are mostly ready and progress in end-to-end AI could potentially enable much faster humanoid robot iteration as seen from the improvement of manipulation and interaction capabilities in 2023
Our evaluation of humanoid robot technology readiness

Components	% of hardware BOM in high-spec robot in2024E	Application	CHN name	Time	Global top players' technology readiness	Domestic top players' technology readiness
AI/Software			**软件**			
Navigation		-	导航	2023	80%	70%
				2022	70%	65%
Manipulation		-	操纵	2023	40% bottleneck	20%
				2022	20%	15%
Interaction		-	交互	2023	50% bottleneck	50%
				2022	45%	30%
Motors						
Frameless torque motor	4%	Linear & Rotary	无框力矩电机	2023	90%	80%
				2022	90%	80%
Coreless motor	6%	Hand	空心杯电机	2023	90%	70%
				2022	90%	65%
Transmission			**直线执行器**			
Planetary roller screw	31%	Linear	行星滚柱丝杠	2023	80% bottleneck	20%
				2022	80%	5%
Trapezoidal screw	2%	Linear	梯形丝杠	2023	80%	50%
				2022	80%	30%
Harmonic reduction gear	4%	Rotary	谐波减速器	2023	90%	80%
				2022	90%	80%
Planetary reduction gear	<1%	Hand & Rotary	行星减速器	2023	80%	80%
				2022	80%	80%
Chips			**芯片**			
Main chip	<1%	-	主芯片	2023	90%	70%
				2022	90%	60%
MCU chip	1%	-	MCU芯片	2023	90%	80%
				2022	90%	75%
Sensors			**传感器**			
Camera	<1%	-	摄像头	2023	90%	80%
				2022	90%	80%
Position sensor	2%	Body	位置传感器	2023	80%	80%
				2022	80%	80%
Inertial Measurement Unit	<1%	Body	惯性导航	2023	80%	60%
				2022	80%	60%
Force sensor	1%	Linear	力传感器	2023	70%	50%
				2022	70%	40%
Torque sensor	1%	Rotary	扭矩传感器	2023	70%	50%
				2022	70%	40%
6D torque sensor	10%	Hand	六维力矩传感器	2023	70%	20% bottleneck
				2022	70%	15%
Tactile sensor	<1%	Hand	触觉传感器	2023	70%	20%
				2022	70%	15%
Others			**其他**			
Battery (kWh)	<1%	-	电池 (kWh)	2023	80%	70%
				2022	80%	70%
Wireless	1%	-	通讯	2023	100%	100%
				2022	100%	100%
Cooling	1%	-	散热	2023	80%	70%
				2022	80%	70%
Drive	2%	-	驱动器	2023	90%	90%
				2022	90%	90%
Encoder	2%	-	编码器	2023	90%	90%
				2022	90%	90%

Note: Different colors represents the degree of technology readiness, with more ready, needing upgrade, less ready corresponding to green, yellow, and red. Bottlenecks are components that have a relatively significant proportion in BOM with low technology readiness for robot mass production.

Source: Company data, compiled by Goldman Sachs Global Investment Research

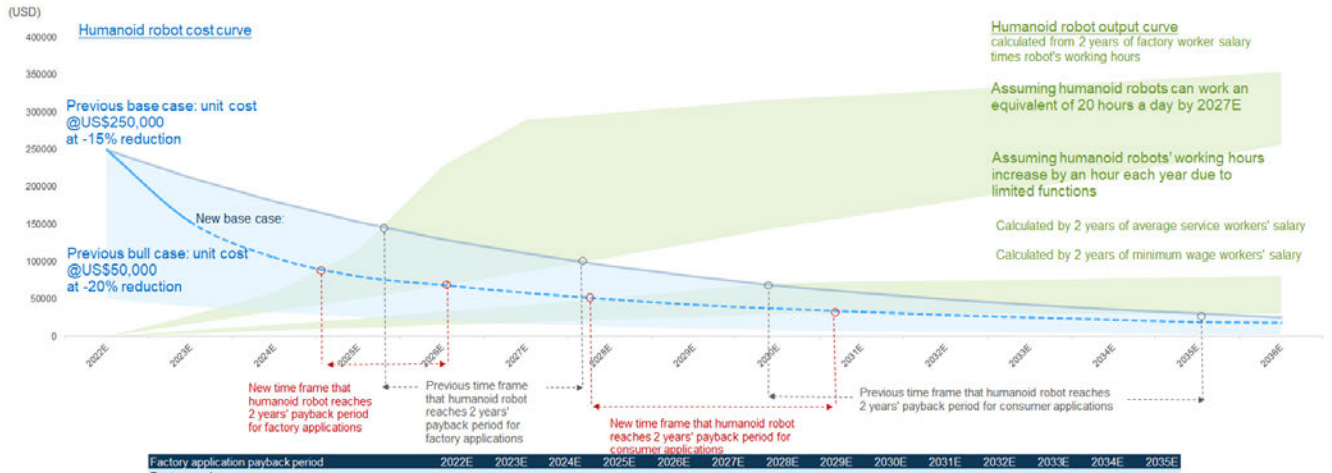
Costs also declined faster to drive better application economics

We note the manufacturing cost for humanoid robot has dropped significantly from likely $50-250k per unit last year to $30-150k (range of low spec to high spec) now, or around 40% decline (vs. our prior assumption of 15% to 20% p.a decline) mainly driven by availability of cheaper components with broader scope of supply chain options from the mere existence in labs previously, optimization in design and manufacturing technique (e.g. cost for T-screw dropped significantly by shifting from electric discharge machining to mechanical machining) which suggests robot commercialization could come faster vs our prior expected timeline based on a payback

period analysis of humanoid robot cost curve vs. output.

Looking forward, we continue to expect further cost reduction in the coming years, especially for high-specs design currently with bottlenecks on a few key components. For example, Tesla adopts planetary roller screws for the linear actuators which can achieve high precision and withstand heavy loads per discussions with planetary roller screw manufacturers such as Hengli Hydraulic and Best precision, however, we believe production capacity and cost reduction depend on (1) availability of key production equipment, esp. high-precision grinding machine with inelastic capacity from suppliers (95% of equipment coming from overseas, such as Japan and Europe) with potential export restrictions (e.g., Japan and some European countries restrict the export of high-end equipment to China); (2) limited technology know-how amongst domestic component makers, as currently overseas players dominate in this special type of product, especially Europe; and (3) high costs as a result of limited industry capacity (serving only niche applications previously, e.g. machine tools and aerospace) and long manufacturing cycle time (1hr or more per piece). That said, according to our channel checks with many potential domestic suppliers (e.g. Best Precision, Hengli Hydraulic, and Sanhua), we believe mass production of humanoid robots could bring down the unit costs of planetary roller screws over time, while domestic substitution is highly determined by equipment capacity, manufacturing technique know-how and talent teams.

Exhibit 13: Our updated assessment suggests factory applications could be economically viable in 2024E-27E (vs. previous expecation of 2025E-2028E) and consumer applications by 2028E-2031E (vs. previous expectation of 2030E-2035E)
Humanoid robot payback period analysis (new vs. prior expectations)



Factory application payback period	2022E	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E	2031E	2032E	2033E	2034E	2035E
Factory workers														
Daily working hours	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Annual working hours	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000	2,000
Hourly wage (USD)	23	24	24	25	26	26	27	27	28	28	29	29	30	31
Inflation rate (%)	5%	3%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Factory worker annual cost (USD)	46,360	47,658	48,802	49,924	51,073	52,094	53,136	54,199	55,283	56,388	57,516	58,666	59,840	61,036
New base case														
Humanoid robot BOM cost (US$)	250,000	152,869	105,485	80,667	68,480	58,220	49,588	42,331	37,051	32,485	28,531	25,104	22,129	19,545
1) Humanoid robot working hours slower ramp up														
Daily working hours	0	1	2	3	4	5	6	7	8	9	10	11	12	13
Annual working hours	0	260	520	780	1,040	1,300	1,560	1,820	2,080	2,340	2,600	2,860	3,120	3,380
Productivity ratio (robot's hours to worker's hours)	0.0	0.1	0.3	0.4	0.5	0.7	0.8	0.9	1.0	1.2	1.3	1.4	1.6	1.7
Humanoid robot 2 years' output (USD)	0	12,391	25,377	38,941	53,115	67,722	82,892	98,642	114,988	131,949	149,542	167,786	186,700	206,303
Payback period (years)	n.a.	24.7	8.3	4.1	2.6	1.7	1.2	0.9	0.6	0.5	0.4	0.3	0.2	0.2
2) Humanoid robot working hours faster ramp up														
Daily working hours	0	2	4	8	16	20	20	20	20	20	20	20	20	20
Annual working hours	0	520	1,040	2,080	4,160	5,200	5,200	5,200	5,200	5,200	5,200	5,200	5,200	5,200
Productivity ratio (robot's hours to worker's hours)	0.0	0.3	0.5	1.0	2.1	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6
Humanoid robot 2 years' output (USD)	0	24,782	50,754	103,843	212,462	270,889	276,307	281,833	287,470	293,219	299,083	305,065	311,166	317,390
Payback period (years)	n.a.	12.3	4.2	1.6	0.6	0.4	0.4	0.3	0.3	0.2	0.2	0.2	0.1	0.1

Consumer application payback period	2022E	2023E	2024E	2025E	2026E	2027E	2028E	2029E	2030E	2031E	2032E	2033E	2034E	2035E
Service workers														
Daily working hours	8	8	8	8	8	8	8	8	8	8	8	8	8	8
Annual working hours	2,080	2,080	2,080	2,080	2,080	2,080	2,080	2,080	2,080	2,080	2,080	2,080	2,080	2,080
New base case														
Humanoid robot BOM cost (US$)	n.a.	152,869	105,485	80,667	68,480	58,220	49,588	42,331	37,051	32,485	28,531	25,104	22,129	19,545
1) Humanoid robot replacing slow-skilled service worker														
US minimum wage (USD)	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25	7.25
Low-skilled service worker annual cost (USD)	15,080	15,080	15,080	15,080	15,080	15,080	15,080	15,080	15,080	15,080	15,080	15,080	15,080	15,080
Humanoid robot daily working hours	0	1	2	3	4	5	6	7	8	8	8	8	8	8
Humanoid annual working hours	0	260	520	780	1,040	1,300	1,560	1,820	2,080	2,080	2,080	2,080	2,080	2,080
Productivity ratio (robot's hours to worker's hours)	n.a.	0.1	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0
Humanoid robot 2 year's ouput (USD)	n.a.	3,770	7,540	11,310	15,080	18,850	22,620	26,390	30,160	30,160	30,160	30,160	30,160	30,160
Payback period (years)	n.a.	324.4	56.0	19.0	9.1	4.9	2.9	1.8	1.2	1.1	0.9	0.8	0.7	0.6
2) Humanoid robot replacing avg service worker														
US service worker average annual salary (USD)	30,045	30,886	31,628	32,355	33,099	33,761	34,436	35,125	35,828	36,544	37,275	38,020	38,781	39,557
Inflation rate (%)	5%	3%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Productivity ratio (robot's hours to worker's hours)	n.a.	0.1	0.3	0.4	0.5	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0
Humanoid robot 2 year's ouput (USD)	n.a.	7,722	15,814	24,266	33,099	42,201	51,654	61,469	71,655	73,088	74,550	76,041	77,562	79,113
Payback period (years)	n.a.	158.4	26.7	8.9	4.1	2.2	1.3	0.8	0.5	0.4	0.4	0.3	0.3	0.2

Note: Our base case cost curve is refering to high spec robots while bull case is refering to low spec robots to account for the technology capability factor to handle the output we assumed.

Source: Goldman Sachs Global Investment Research

Considering current technology capabilities, **we view humanoid robot has visible demand from works in structured environment such as manufacturing (e.g. EV assembly and component sorting).** Per UBTech (9880.HK. non-covered), 70% of the overall current manufacturing work in China is handled by existing machinery & automation solutions, 20% is still handled by manual labor and 10% is handled by management staff. Together with the existing industrial robot products which can perform more rigid and precise tasks, we expect humanoids, being more flexible and capable of adapting to complex terrain vs. flat ground, can also help tackle the incremental automation TAM.

Given its likely adaptability to dynamic environment enabled by AI algorithms, **humanoids look particularly appealing for special operations such as "dangerous,** dirty and dull" **(3D) tasks,** considering the associated fatality rate and people's low

willingness in doing such jobs thus customers' likely willingness to pay a higher price than typical manufacturing work. According to US Bureau of labor statistics, fatal work injuries recorded in US is around 5,000 per year and fatal work injury rate is c3.5 per 100k workers. Taking coal mining as an example, fatality rate in US/China is at 16.2 per 100k FTE (Full-time equivalent employees) and 0.04 per mn ton of coal as of 2021. Other possible applications are: disaster rescue, nuclear reactor maintenance and chemicals manufacturing. Along with auto manufacturing, as a sensitivity test, **assuming 5%/10%/15% labor substitution rate for these five applications, humanoid robot demand can potentially reach 1.1mn-3.5mn units globally.** The need for robots to handle hazardous/dangerous jobs is already elevated by national policy. On Jan 5, 2024, the Ministry of Emergency Management and Ministry of Information & Technology in China jointly announced their plan to develop emergency robots, which are intelligent robots that perform tasks such as monitoring and providing early warnings, search and rescue, communication command, logistics support, safety production operations, and disaster relief.

According to our Asia Industrials Analyst Isayama Yuichiro's takeaways from International Robot Exhibition, Japanese robot OEMs are also dedicated to launch a diverse range of solutions for more non-conventional applications. For example Kawasaki Heavy Industries showed a demo of its Kaleido humanoid robot, potentially suitable for disaster rescue.

Exhibit 14: Existing global humanoid robot brands, product specs and their targeted applications

Global ex-China humanoid robots									
Manufacturer	Boston Dynamics	Agility Robotics	Tesla	Apptronik	Kawasaki Heavy Industries	Rainbow Robotics	1X	Figure	Sanctuary AI
Model	*Atlas* 	*Digit (Latest Gen)* 	*Optimus Gen 2* 	*Apollo* 	*Kaleido* 	*HUBO2* 	*EVE* 	*Figure 01* 	*Phoenix* 
Mass	89kg	<65kg	63kg	73kg	80kg	43kg	83kg	60kg	70kg
Height	1.5m	1.75m	1.72m	1.73m	1.80m	1.20m	1.83m	1.70m	1.70m
Speed	2.5m/s	1.5m/s	2.0m/s	1.0m/s	1.1m/s	0.5m/s	3m/s	1.2m/s	1.2m/s
Degrees of freedom	28	10 + 8 (arms)	28 + 22 (hands)	c.30	34	32	74	41	74
Continuous operating time	1hr	16hr (optimized for logistics)	4hr	4hr	n.a.	n.a.	4hr	5hr	n.a.
Country	USA	USA	USA	USA	Japan	Korea	Canada	US	Canada
Target applications									
Disaster rescue	✓				✓	✓			
Special/hazardous applications	✓		✓	✓	✓	✓			
Patrol							✓		
Logistics	✓	✓		✓			✓	✓	✓
Auto manufacturing			✓	✓					
Healthcare/elderly care			✓	✓			✓	✓	✓
Commercial applications	✓		✓	✓		✓		✓	✓

Robot models are updated as of Jan 5, 2024.

Source: Company data, Data compiled by Goldman Sachs Global Investment Research

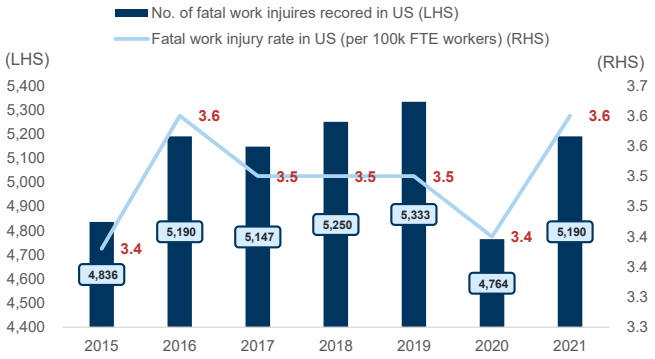
Exhibit 15: China humanoid robot brands, their product specs and targeted applications

China humanoid robots										
Manufacturer	UBTECH	Fourier Intelligence	AGIBOT	Unitree	Dataa	Xiaomi	Dreame	Chunmi	Leju Robot	KEPLER
Model	Walker S	Fourier GR-1	Expedition A1	H1	XR-4	CyberOne	Universal Humanoid Robot	DaQiang	KUAVO	K1, S1, D1
Mass	n.a.	60kg	55kg	47kg	65kg	52kg	56kg	65kg	65kg	85kg
Height	1.70m	1.65m	1.75m	1.8m	1.68m	1.77m	1.78m	1.70m	n.a.	1.78m
Speed	n.a.	1.4m/s	1.9m/s	>1.5m/s	1.4m/s	1.0m/s	0.6m/s	0.6m/s	1.3m/s	n.a.
Degrees of freedom	41	44	49+	20	60+	21	44	36	26	28 + 12 (hands)
Continuous operating time	2hr	>1hr	n.a.	2hr	12hr	2hr	n.a.	n.a.	n.a.	n.a.
Country	China	China	China	China	China	China	China	China	China	China
Target applications										
Disaster rescue									✓	✓
Special/hazardous applications									✓	✓
Patrol			✓						✓	✓
Logistics	✓		✓	✓					✓	✓
Auto manufacturing	✓		✓	✓					✓	✓
Healthcare/elderly care	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Commercial applications	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Robot models are updated as of Jan 5, 2024.

Source: Company data, Data compiled by Goldman Sachs Global Investment Research

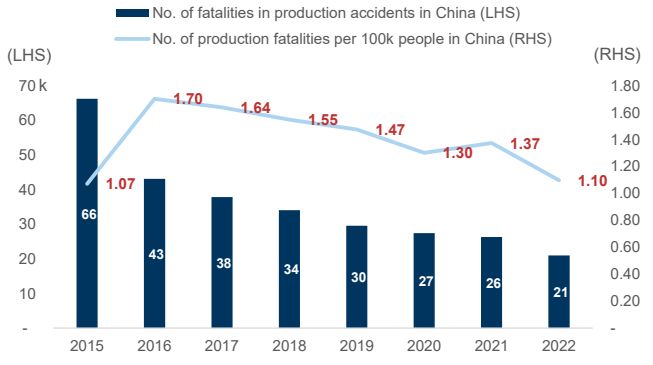
Exhibit 16: US Bureau of labor statistics recorded fatal work injuries in US at c.5,000 and fatal work injury rate at c3.5 per 100k workers...
US 2015-2021 work injuries statistics



FTE workers: Full-time equivalent (FTE) employees computed using reported hours worked (2,000 hours = 1 FTE)

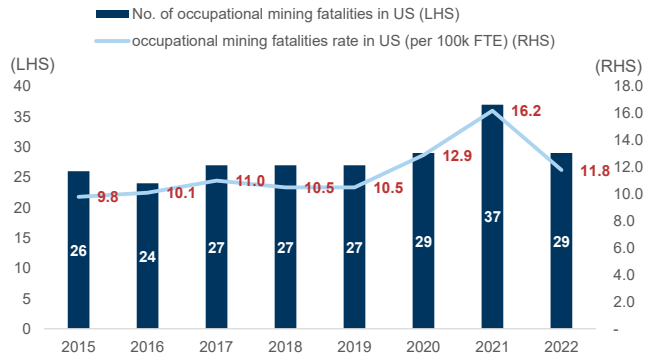
Source: US Bureau of Labor Statistics, Data compiled by Goldman Sachs Global Investment Research

Exhibit 17: ... and the same indicators for production activities came at 21k/1.1 in 2022 for China
China 2015-2022 production activities fatalities statistics



Source: NBS, Data compiled by Goldman Sachs Global Investment Research

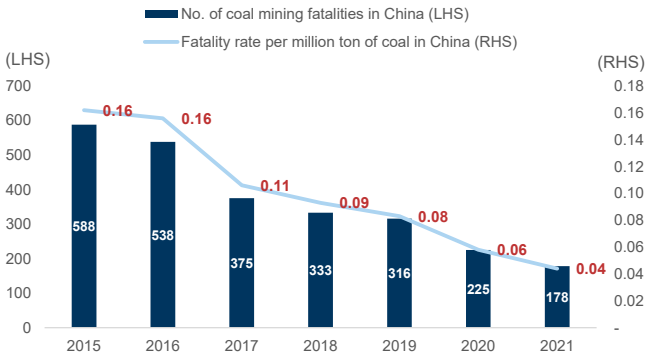
Exhibit 18: No. of fatalities of coal mining in 2021 in US came at 37, with fatalities rate at 16.2 per 100k FTE...
US 2015-2022 coal mining fatalities statistics



FTE: Full-time equivalent (FTE) employees computed using reported hours worked (2,000 hours = 1 FTE)

Source: Statista, CDC, US Bureau of labor statistics, Data compiled by Goldman Sachs Global Investment Research

Exhibit 19: ...and China in 2021 had 178 fatalities in coal mining, with fatalities rate at 0.04 per mn ton of coal
China 2015-2021 coal mining fatalities statistics



Source: NBS, Data compiled by Goldman Sachs Global Investment Research

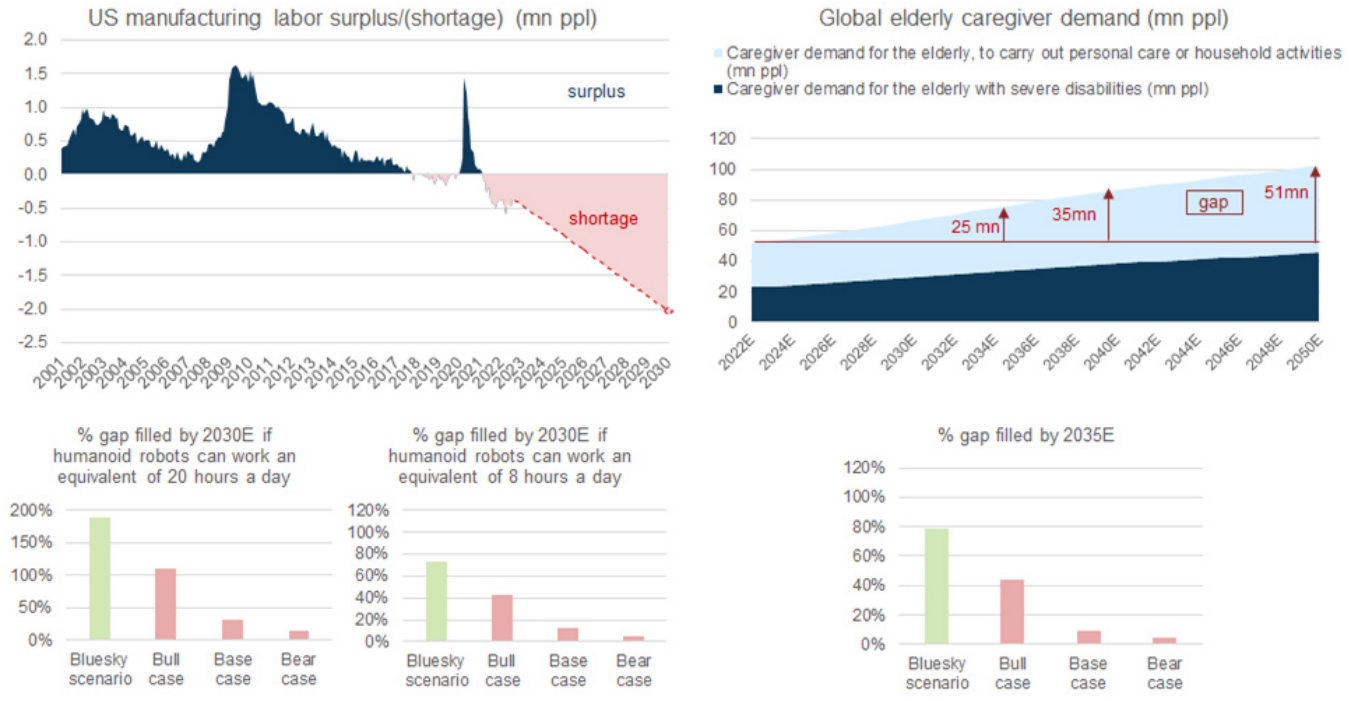
Exhibit 20: As a sensitivity test, humanoid robot demand could reach 1.1mn-3.5mn units globally assuming 5%/10%/15% substitution rate of hazardous and dangerous works as well as auto manufacturing

	Humanoid robot demand from labor force substitution (k units)					
	at 5% substitution rate		at 10% substitution rate		at 15% substitution rate	
	Global ex. China	China	Global ex. China	China	Global ex. China	China
Special operations	**500**	**213**	**1,000**	**426**	**1,499**	**639**
Disaster rescue	*70*	*19*	*140*	*38*	*211*	*58*
Nuclear reactor maintenance	*9*	*2*	*18*	*3*	*26*	*5*
Coal mining	*384*	*130*	*769*	*260*	*1,153*	*390*
Hazardous chemical industry	*36*	*62*	*73*	*125*	*109*	*187*
Auto manufacturing	**215**	**219**	**430**	**437**	**645**	**656**
Total	**715**	**431**	**1,430**	**863**	**2,145**	**1,294**

Source: US Bureau of Labor Statistics, Statista, DATAUSA, The World Bank, ACEA, NBS, World Nuclear Association, IAEA, heneng.net, Goldman Sachs Global Investment Research

With that said, we would need to monitor the industry development for a longer time to evaluate humanoid robot's capability to handle generalized multi-task applications. Put in another word, **it is still a question whether a general purpose AI robot is technologically viable** to handle consumer/household applications such as elderly care.

Exhibit 21: If general purpose AI robot is technologically/economically viable, it could greatly solve social issues such as manufacturing labor shortage and elderly care etc.



Source: OECD, Deloitte, FRED, Goldman Sachs Global Investment Research

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Reg AC

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