www.springer.com/41230
https://doi.org/10.1007/s41230-024-4141-3
Special Review
Vol. 21 No. 5 September 2024
CHINA FOUNDRY

# Lightweight innovation ADIs help development of renewable energy and new technology industries in China

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**Received: 2024-07-25**
**Accepted: 2024-08-20**

**Abstract:** The world is undergoing profound changes in energy and technology. Countries are vigorously developing new sustainable energy sources and technologies. Renewable energy sources encompass various technologies such as wind turbines, solar energy, nuclear energy, and bioenergy. Additionally, emerging technology fields include new energy vehicles, robots, and artificial intelligence devices, among others. The renewable energy industries and implementation of new technologies necessitate the development and adoption of new equipment and components. Austempered ductile iron (ADI) is renowned for its unique microstructure and superior properties. By utilizing ADI, lightweight and innovative castings can be designed to not only reduce weight but also save energy and decrease emissions. More importantly, these castings enhance the efficiency and reliability of new energy equipment and emerging technology installations. This paper describes the development, applications, and future prospects of lightweight and innovative ADI castings within sectors such as solar photovoltaic (PV), wind power generation, industry robots, and trucks in China.

**Keywords:** lightweight; ADI; renewable energy; emission reduction

**CLC numbers:** TG143.5; **Document code:** A;

**Article ID:** 1672-6421(2024)05-507-09

## 1 Introduction

### 1.1 Global clean sources continue to develop rapidly

Although some of the direct pressures brought about by the global energy crisis have been alleviated, the energy market, geopolitics, and global economy remain unstable, and there is always a risk of further destruction. Nowadays, the world's average global temperature is 1.2 °C higher than in pre-industrial times [1], leading to the occurrence of heatwaves and other extreme weather events. Furthermore, greenhouse gas emissions have not yet peaked. The energy sector is identified as the primary source, contributing to over 90% of the global population being exposed to polluted air, which results in more than 6 million premature deaths annually. In some countries, the positive progression towards enhancing electricity supply and clean cooking practices has been decelerated or even reversed [1].

In this complex context, the emergence of a new clean energy economy led by solar photovoltaics and electric vehicles has brought hope for the path forward. Since the year 2020, there has been a 40% increase in investment towards clean energy [1]. While promoting emission reduction is a key motive, it is not the sole reason behind this uptick. Mature clean energy technologies offer compelling economic incentives. Energy security also plays a crucial role, particularly in countries that import fuel, where industrial strategies and the objective to generate employment opportunities in the clean energy sector are equally significant. Not all clean technologies are flourishing, some supply chains, especially wind energy supply chains, are also facing pressure. However, there are also some notable examples indicating that the pace of change is accelerating. In 2020, one out of every 25 cars sold was an electric vehicle [1]. Figures for 2023 are not yet available, but it is expected that the proportion will be one-fifth. More than 500 gigawatts (GW) of renewable energy generation capacity are expected to be added for 2023, setting a new record. The deployment of solar energy costs over $1 billion per day [1]. The manufacturing capacity of key components for clean energy systems, including solar photovoltaic modules and electric vehicle batteries, is rapidly expanding. That is why the International Energy Agency recently concluded in its updated net zero emissions roadmap that limiting global warming to 1.5 °C is very difficult, but this path is still open and achieving the goal is still foreseeable [1].

A report released by London Think Tank Ember on 8 May 2024 shows that billions of people use different types of energy every day, and 2023 was a record-breaking year for renewable energy, which does not emit pollutants such as carbon dioxide and methane that cause global warming [2].

## 1.2 Electricity from clean sources reaches 30% of global total in 2023

In 2023, for the first time, 30% of electricity produced worldwide was from clean energy sources as the number of solar and wind farms continued to grow rapidly, as shown in Fig. 1. Last year, hydroelectric dams generated the most clean energy, a trend consistent with most years. However, droughts in India, China, North America, and Mexico led to a five-year low for hydropower production. Studies indicate that climate change is accelerating the onset and intensity of droughts [2].

## 1.3 The fastest growth in solar and wind power generation in 2023

The year 2023 is the fastest growing year for solar and wind power generation globally, significantly exceeding the increase in fossil fuels, as shown in Fig. 2 [2]. It is believed that due to policy support from various governments, the growth rate of global solar and wind power generation will be faster in the future. In 2023, electric vehicles, heat pumps, air conditioning, and data centers accounted for more than half of the total electricity consumption, as shown in Fig. 3 [2].

## 1.4 China added the most clean energy in the world in 2023

In 2023, among countries around the world, China added most clean energy, as shown in Fig. 4. However, China also accounts for 55% of global coal power generation, with nearly 60% of China's electricity generation coming from coal [2].

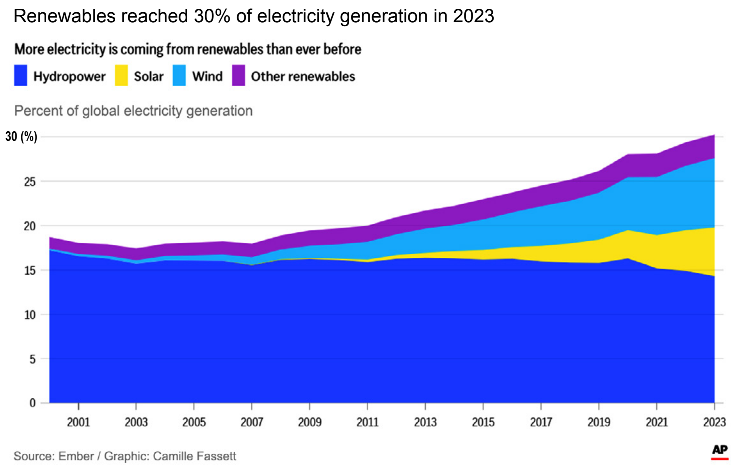


**Fig. 1: In 2023, renewables reached 30% of total electricity generation for the first time [2]**

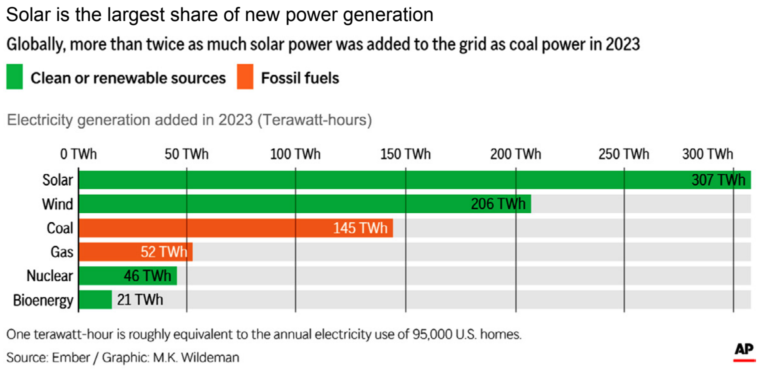


**Fig. 2: The fastest growth in solar and wind power generation in 2023 [2]**

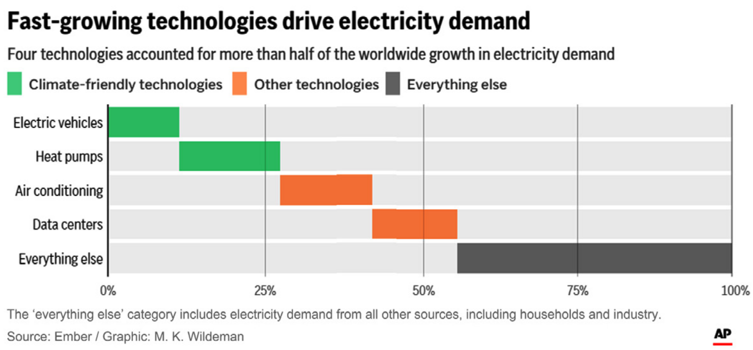


**Fig. 3: Rapid growth in technology driven demand for electricity [2]**

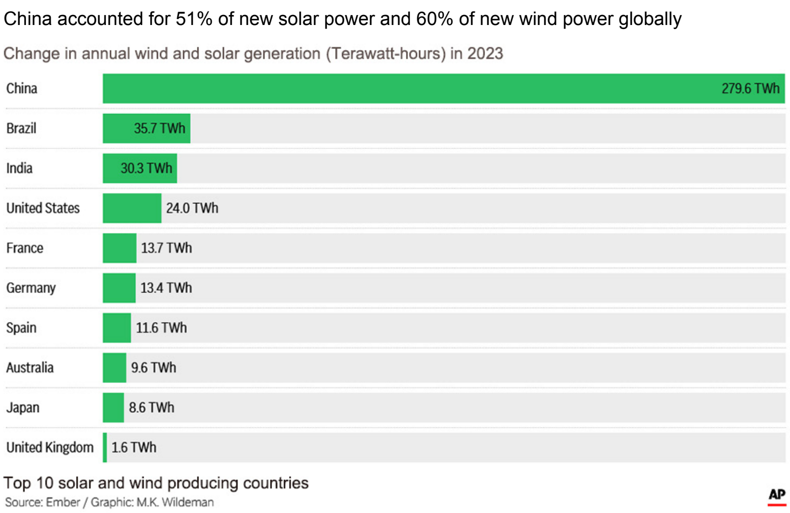


**Fig. 4: China added far more clean power than other countries in 2023 [2]**

The China Electric Power Development Report 2023 released by the Electric Power Planning and Design Institute showed that in 2022, the national power generation reached 8.7 trillion kilowatt hours, with non-fossil energy generation reaching 36.2% [3]. At present, the proportion of clean power generation in China is still lower than that of other developed countries, necessitating continued rapid development.

### 1.5 With the unique microstructure and superior performance, ADI can play an important role in the new energy and new technology industries

Within the cast iron family, austempered ductile iron (ADI) has a unique microstructure and an excellent, optimized combination of mechanical properties. The main microstructure of ADI is ausferrite, which is a mixture of extremely fine acicular ferrite and stable, high-carbon austenite. There are two types of austenite in ADI: (1) the coarser and more equiaxed blocks of austenite between non-parallel acicular structures, which exist mainly in the last solidified area, and (2) the thin films of austenite between the individual ferrite platelets in the acicular structure. This unique microstructure gives ADI excellent static and dynamic properties, as well as good low-temperature impact toughness [4-6].

In recent decades, the automotive industry has been transitioning from a heavy reliance on iron castings to aluminum castings, a trend that persisted in subsequent years. However, cast iron, especially ADI, exhibits the lowest relative weight per unit yield strength and fatigue limit (stress under which failure does not occur regardless of the number of cycles), compared with aluminum. More importantly, the specific stress (stress/density) of ADI is superior to that of aluminum alloys when the number of cycles exceeds $10^7$. In addition, ADI's high strength-to-weight ratio and high stiffness enable it to replace materials like aluminum or magnesium at equal mass in sections exceeding 3 mm. Furthermore, its low embodied energy and recyclability give it superior sustainability compared to steel, aluminum and magnesium [4-6].

Considering its nanometer grain size, unique microstructure, excellent mechanical properties, and good castability (which allows for the cost-effective, high-volume production of near net shape components), as well as the fact that it can be 100% recycled, it is not overemphasized to describe ADI as a high-tech, nanometer-scale, and environmentally friendly material. ADI possesses potential for further enhancement, and both its production and the range of applications are expected to expand, driven by the resultant cost savings over alternative materials [4-6].

New energy technology sectors necessitate innovative equipment and components. With its unique microstructure and excellent properties, lightweight innovative ADI components can help the development of these industries. The following sections describe the development and applications of lightweight, innovative ADI in areas such as solar PV, solar thermal and wind power, intelligent robots, and new energy vehicles, as well as their development prospects.

## 2 Application of lightweight and innovative ADI in solar PV tracking system

A solar tracking system monitors the sun's trajectory throughout the day, automatically modifying the orientation of solar panels. This adjustment optimizes the angle at which sunlight strikes the panels, considering both azimuth and elevation, thereby enhancing energy production [7-13]. Solar tracking systems have been in use for decades, and the earliest known device can be traced back to the 1970s. Early systems were mainly used for large solar power plants and research facilities. It has now been widely used in ordinary solar photovoltaic power generation [7]. There are three main types of solar tracking systems: fixed axis, single axis, and dual axis systems. Fixed axis systems are the simplest and cheapest, and their efficiency is limited because they are fixed at a certain angle without any movement. The single axis tracking system follows the sun's motion from east to west, significantly boosting energy yield. In contrast, the dual axis tracking system can track both the east-west trajectory and the seasonal variations of the sun, ensuring the highest possible energy production. Figure 5 shows the three types of dual axis tracking systems. Compared with fixed tilt systems, dual axis tracking systems can increase energy production by 30%–40% [8], or 45% [9], even 56% [10].

Implementing solar tracking systems may lead to higher initial installation expenses, but the long-term benefits derived from increased energy production can offset these costs. As technology advances and associated costs decline, the adoption of tracking systems is becoming more widespread.

The study of ADI components for solar PV tracking systems started as early as 2014 in China. At that time, a client from abroad placed

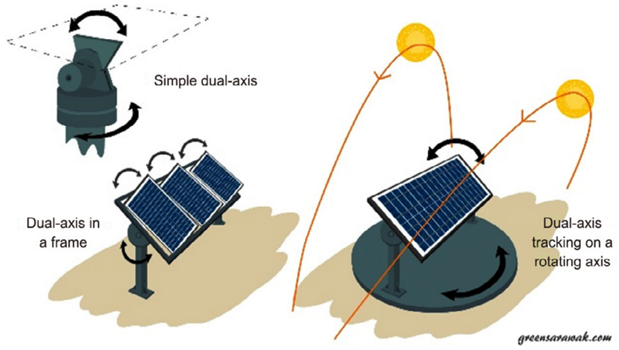


**Fig. 5: Three types of dual axis sun tracking systems**

an order with Changjian Foundry in Kunshan City, Jiangsu Province, China for tracker reduction gear components. The parts ordered were forged steel assemblies. The reduction gears were machined from 50Mn steel forgings, while the worm was made from 42CrMo steel forgings and then subjected to a quenching and tempering treatment, achieving a surface hardness exceeding 550 HV. After machining, the gears and worms were assembled into a single worm-gear component using fastening bolts. After conducting a study, the technical team of the foundry proposed that ADI castings may be a more suitable material for this component, not only to reduce costs, but also to fully meet the functional requirements. Following research, the original steel assembly was converted into a single cast part. Figure 6 shows the original steel fabrication design and the redesigned single casting. Through strict control of ductile iron casting quality, precision pre-machining, austempering treatment, and final machining, the desired quality of the ADI worm component was obtained. After performance testing and installation experiments, it was verified that ADI is a very suitable material for turbine shafts, offering approximately 30% cost reduction. Mass production began in 2015. Subsequent optimizations have reduced the thinnest wall thickness of the solar PV reduction gear to 8 mm. However, due to the superior wear resistance of ADI, its lifespan can still reach designed 30 years.

At present in China, there are six foundries producing ADI castings for solar PV tracking systems with more than 30 varieties, weighing 5–50 kg and having a wall thickness from 8 mm to 35 mm. According to incomplete statistics by the ADI committee of the China Foundry Association, a total weight of approximately 10,500 tons of ADI castings for solar PV power tracking systems were produced in 2023. The main grades were QTD1400-2L and QTD1050-7. The solar PV power worm gear reducer is shown in Fig. 7. A typical ADI worm casting and machined component are shown in Fig. 8.

At present, several top 10 solar PV tracker manufacturers abroad, including Nextracker, have adopted ADI parts. Similarly, several domestic top 10 solar PV tracker producers, including Arctech Solar in Suzhou China, also have adopted ADI parts. It is understood that in the USA, 90% of new solar

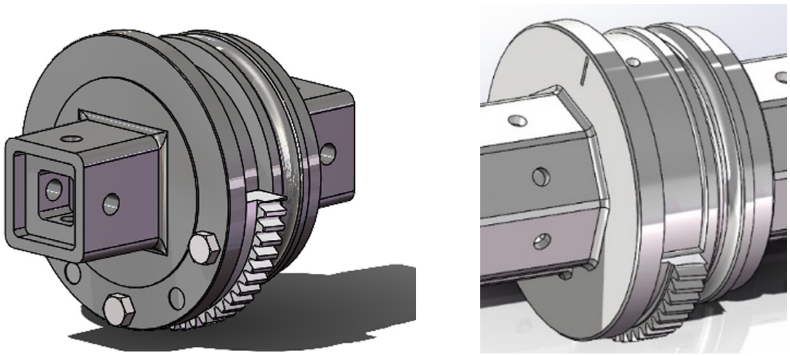

**Fig. 6: Original design of steel fabrication tracking worm gear (left) and the redesigned single ADI casting (right) (courtesy Changjian Foundry)**

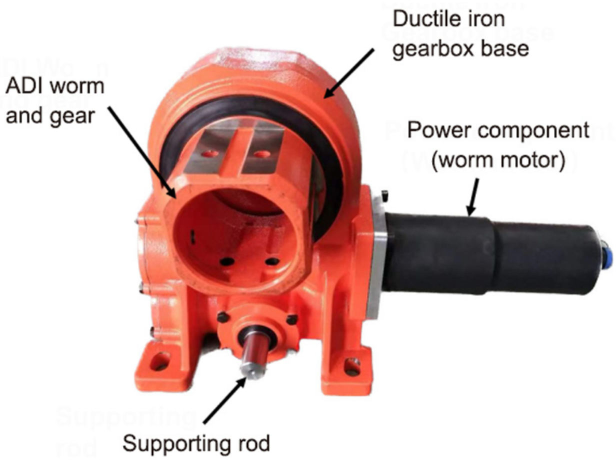


**Fig. 7: ADI worm and gear used in reducer for solar PV trackers (courtesy Hongxiang Foundry)**

**Fig. 8: Raw casting (left) and machined (right) ADI worm parts for solar PV trackers (courtesy Changjian Foundry)**

PV installations in 2021 were equipped with trackers, bringing the cumulative total to 80%. The solar market compound annual growth rate (CAGR) is expected to be 8% over the next three decades.

In addition to solar PV generation, there is also a technology that converts solar radiation energy into electrical energy, namely solar thermal power generation. Solar thermal power is achieved through an intermediate process of thermal energy conversion. Initially, solar radiation energy is concentrated into a small area through a focusing system, which then heats and circulates the working medium (such as water or other suitable fluid) to generate steam. This steam is transformed into mechanical energy within a turbine, powering the generator to produce electricity.

China's solar thermal power generation started relatively late, and at present only occupies a relatively small proportion in the world. However, due to increased government support, it has developed rapidly in recent years.

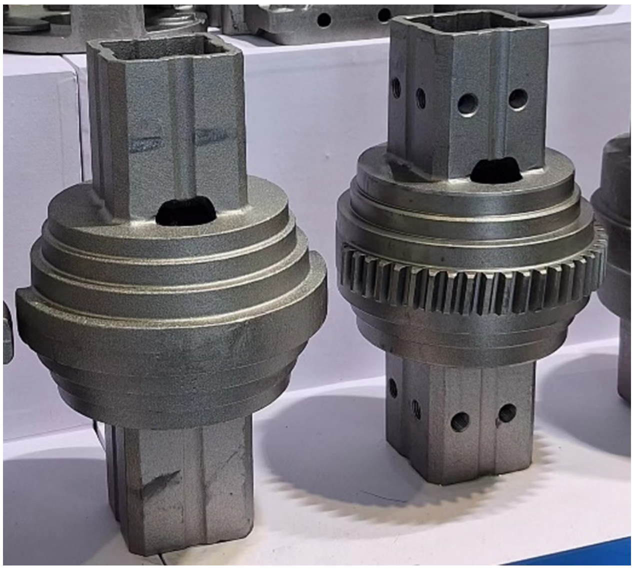

**Fig. 9: ADI worm casting (left) and machined component (right) used in tracking systems for solar thermal power and PV power (courtesy Haian Wanli Foundry)**

The solar thermal power generation system has a tracking system that can focus sunlight on the receiver throughout the day when the position of the sun in the sky changes. The tracking system for solar thermal power may need higher accuracy than that of solar PV. Some Chinese foundries have supplied ADI components for solar thermal power tracking systems. Some tracking systems can be used both for solar PV and solar thermal power. One example of such type of ADI components used for both systems is shown in Fig. 9. The adoption of ADI castings in solar thermal tracking systems is significantly lower compared to their use in solar PV systems. However, as designers become more aware of the benefits offered by ADI castings, it is anticipated that their application in the solar thermal power sector will experience rapid growth.

As far more PV power installations are added than any other countries and solar thermal power installations are rapidly increasing, China has a high demand for solar PV and solar thermal power generation trackers. There is a great market potential for solar PV and solar thermal power generation trackers and ADI castings.

## 3 Application of lightweight and innovative ADI in wind turbines

Research has shown that, with its unique performance, ADI is a suitable material for planetary carriers used in wind turbine transmissions [14,15]. The optimized design of an ADI planetary carrier may have a reduced weight of 17% [15], and still meet the required performance criteria. An ADI planetary carrier weighing 7 tons in a wind turbine gearbox, has already been adopted in Europe and China. Figure 10 shows an ADI planetary carrier undergoing austenitization treatment by ADI treatments in Birmingham, UK [16] and planetary carriers austempered by a commercial heat treater in Shiyan, Hubei, China.

However, according to incomplete statistics by the ADI Committee of the CFA, a total weight of 604 tons of ADI castings for wind power mill were produced in 2023. The application of ADI castings is very small and needs to be studied and expanded.

(a)

(b)

**Fig. 10: ADI planetary carrier undergoing austenitization treatment at ADI treatments in Birmingham, UK (a) [16], and ADI planetary carriers heat treated by Hubei ADI Material Tech Co., Ltd., Hubei Province, China (b)**

Driven by the global demand for clean energy, wind turbines have been increasing in power in recent years, with Vestas offshore wind turbines reaching a maximum of 15 MW. It has been reported recently that Siemens Gamesa has plans to produce a 21 MW model in the next few years [17]. As the power of wind turbines has increased, the size and weight of the gearbox has actually decreased due to improvements in design and optimized material usage.

As the weight of the gearbox decreases with the increase of torque density, the requirements for material performance become increasingly high. In addition to conventional tensile strength, elongation, and impact toughness, fatigue limit is often an increasingly important factor to consider. Moventas Gears believes that considering ADI-2 (EN GJS-900-8) and ADI-3 (EN-GJS-1050-6) for transmissions is a feasible option [18].

# 4 Lightweight and innovative ADI gears in industrial robots

In recent years, the wave of artificial intelligence has swept through, and artificial intelligence will become the main feature of the fourth industrial revolution. Many artificial intelligence applications require mechanical devices to perform actions and complete intelligent tasks. This has driven the rapid development of the industrial robot market.

The operation of industrial robots is mainly controlled by three components: servo motor, reducer, and controller. The gear speed converter of the robot reducer is used to reduce the motor's rotation to the desired level and obtain greater torque. At present, the common types of robot reducers are mainly divided into two categories: RV reducers, which are installed in high-load positions such as industrial robot arms and shoulders, and harmonic reducers, which are placed in low-load positions like forearms, wrists, and palms.

The Zhengzhou Machinery Research Institute has adopted a viable and optimized precision casting process to produce high-quality ductile iron billets with high internal density, free from defects such as shrinkage or porosity. This ensures that the dimensional accuracy of gear blanks remains stable, achieving a CT7 level. An austempering quenching salt bath furnace that can precisely control the austempering temperature, has been developed, ensuring high quality and consistency of the products. The locations of gears in industrial robots, RV reducer, and ADI gears in industrial robots are shown in Fig. 11 [20]. The production trial of the RV reducer ADI gear has achieved good results in the installation test, achieving the goal of stable production [20].

Xi'an University of Technology and Shaanxi Tongxin Continuous Casting Company collaborated for many years to study robot harmonic ADI gears, as shown in Fig. 12. Laboratory experiments and installation trials of the robot harmonic ADI gear demonstrate that it exhibits extremely low noise and excellent wear resistance, achieving satisfactory results.

ADI possesses adequate strength, superior wear resistance, and low noise characteristics. Furthermore, ADI gears are at least 9% lighter compared to their steel counterparts. The use

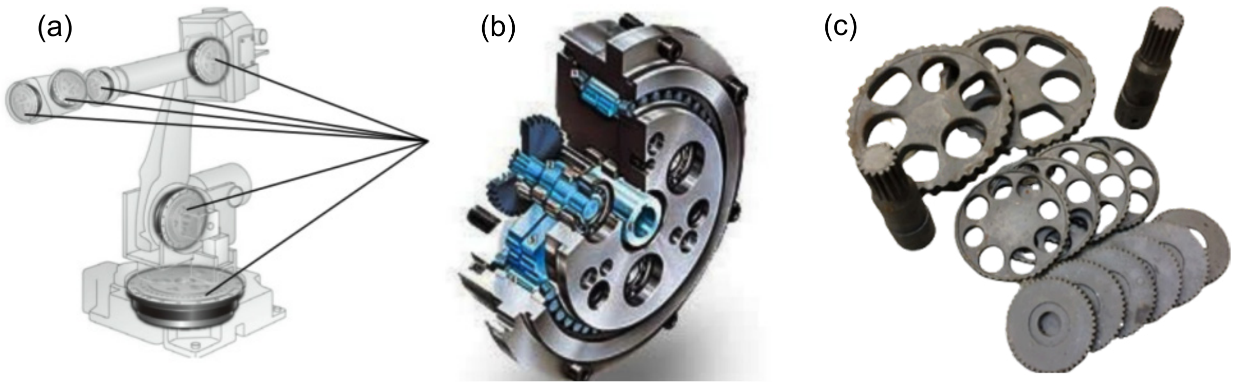


**Fig. 11: Location of gears in industrial robots (a), RV reducer (b), and ADI gears in industrial robots (c) [20]**

**Fig. 12: ADI harmonic gears used in industrial robots. (courtesy Shaanxi Tongxin Continuous Cast Tube Tech)**

of ADI gears in industrial robots requires further exploration. As the utilization of industrial robots expands across various manufacturing sectors, ADI gears present a promising prospect for future growth.

## 5 Application of lightweight innovation ADI components in electric trucks and other trucks

In China, heavy-duty trucks (HDTs) represent only about 3% of the national vehicle fleets. However, the carbon emissions from a single diesel HDT are equivalent to almost 100 passenger vehicles. Additionally, diesel HDTs produce significant amounts of nitrous oxides ($NO_x$) and particulate matter (PM), accounting for 85% and 65% of total vehicle emissions, respectively [21].

As new electric trucks gradually occupy the market, more and more drivers choose this emerging mode of vehicle transport. This is due to the advantages of a long driving range (up to 300 kilometers), which is sufficient for drivers who frequently engage in short distance transportation. Also, higher power, faster acceleration and faster driving speed, enable more efficient mining transportation compared to traditional internal combustion engine driven trucks. This results in lower operating costs, longer lifespan, and can achieve lower transportation costs.

Weight-saving is the important way for new energy vehicles to increase their driving range. Saving weight can effectively improve the handling and power of the entire vehicle, enhance acceleration performance of the vehicle, and shorten the braking distance.

In China, leading automobile manufacturers and components suppliers consider the lightweighting of automotive parts, including truck components, as a crucial indicator of enhancing vehicle functionality and competitiveness. Figure 13 shows original suspension components of a certain Dongfeng model electric truck weighed 119.74 kg converted to a re-designed, lightweight ADI part, which weighs only 69.75 kg, reducing the weight by almost 50 kg, saving 42%. Figure 14 shows a lightweight innovative ADI cross-member in electric trucks replaced a steel stamping, eliminating 32 pairs of bolts and nuts. The total weight of the cross member was reduced from 91 kg of the original steel stamping to 49 kg of ADI cross-member.

Electric vehicles play the most important role in reducing greenhouse gas (GHG) emissions and the impact of global warming. However, electric vehicles are only part of the answer. For areas where electrification is not a realistic option – especially hard-to-abate sectors such as aviation and shipping, low-carbon or zero carbon fuel for internal combustion engines will be essential. The reality is that fossil-fueled internal combustion engines (ICEs) are going to dominate for many years to come [21].

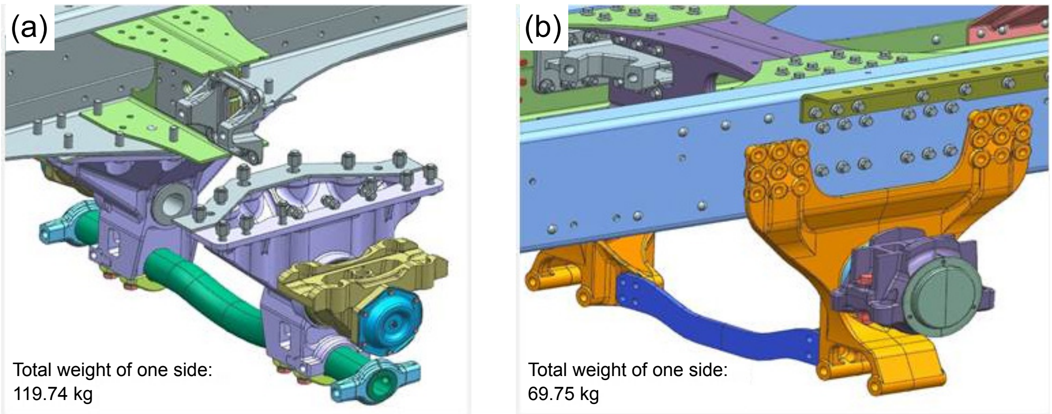


**Fig. 13: Original suspension components of a certain Dongfeng model electric truck weighed 119.74 kg (a), and re-designed, lightweight ADI assembly weighs only 69.75 kg, reducing the weight by almost 50 kg, saving 42% (b) (courtesy Jiangsu Townsun)**

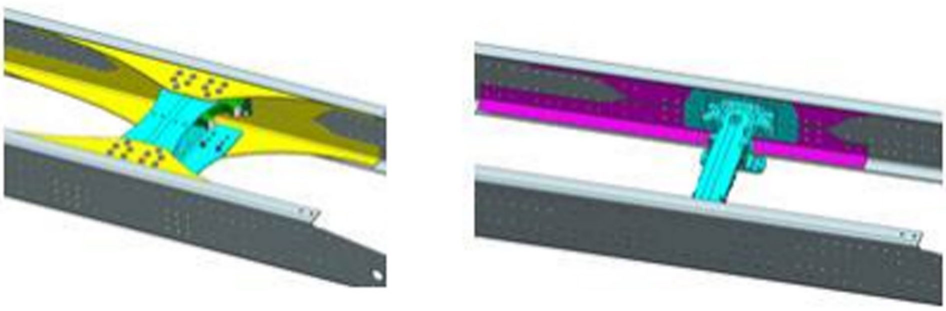

**Fig. 14: Lightweight innovative ADI cross-member (right) replaced a steel stamping (left), eliminating 32 pairs of bolts and nuts. The total weight of the cross member was reduced from 91 kg (original steel stamping) to 49 kg (ADI cross-member) (courtesy Jiangsu Townsun)**

Dongfeng Motor collaborated with Austemper Suzhou, a commercial ADI treatment company, to explore the application of lightweight, innovative ADI components in the chassis suspension of an internal combustion engine-powered off-road truck [22]. Computer-aided Engineering (CAE) tools for redesigning the structure of components and grade 1050 ADI were used in this study. The total weight of the final ADI suspension components for an off-road truck was 415 kg, which is approximately 150 kg lighter than a comparable conventional steel casting chassis (a saving of 26.5%).

The vehicle passed a 20,000 km road endurance test. In addition to intensive benchmark testing, power, operation, safety, reliability and further endurance testing were completed. All the performance criteria met national and industrial specifications. All ADI components passed benchmark and road testing successfully. In addition, the truck's mobility was greatly improved. Figure 15 shows the final off-road truck chassis ADI components.

According to incomplete statistics by the ADI Committee of CFA, in 2023 a total weight of approximately 19,960 tons of ADI castings was used for road transportation by electrical trucks and internal combustion engine powered trucks.

According to the data of the China Association of Automobile Manufacturers, in 2023, the cumulative sales of heavy-duty


**Fig. 15: Final lightweight off-road truck chassis ADI components, which are 26.5% lighter than a comparable conventional steel casting chassis**

trucks reached 910,000 units, and the cumulative sales of medium-duty and light-duty trucks reached 200 million units [23]. When considering these truck sales, the use of ADI castings is still very small and needs to be further expanded.

It is anticipated that as the improvement of ADI manufacturing technology continues in China, engineers will further expand the design and use of ADI for more and more automotive structural parts.

## 6 Summary

(1) Global, new clean energy industries continue to develop rapidly, with solar PV, solar thermal power and wind power being the fastest growing renewable energy sources.

(2) Due to the unique microstructure and excellent properties of ADI, lightweight and innovative ADI components have been deployed in solar PV, solar thermal and wind power industries. These help development of renewable source industries, and have great growth potential.

(3) Lightweight and innovative ADI components have been used in new technology industries such as robotics and electric vehicles, and have a great application future.

## Acknowledgments

The authors would like to thank Shaanxi University of Technology, Haian Wanli Foundry Co., Ltd., Shaanxi Tongxin Continuous Cast Tube Tech Co., Ltd., Hubei ADI Material Tech Co., Ltd., Jiangsu Hongxiang Machinery Manufacturing Co., Ltd., Jiangsu Townsun Auto Parts Co., Ltd., and Zhengzhou Machinery Research Institute for their information in the preparation of this work.

## Conflict of interest

Dr. Jin-cheng Liu is an EBM of *CHINA FOUNDRY.* He was not involved in the peer-review or handling of the manuscript. The authors have no other competing interests to disclose.

## References

[1] International Energy Agency (IEA), World energy outlook 2023, Oct. 24, Paris France. https://www.iea.org/events/world-energy-outlook-2023.

[2] O'Malley I. More and faster: Electricity from clean sources reaches 30% of global total. https://apnews.com/article/renewable-energy-climate-solar-wind-fossil-fuels-2718fce0ed37232dc25dbf46fff87955, updated May 9, 2024.

[3] The proportion of non-fossil energy power generation in our country reached 36.2%. https://www.gov.cn/yaowen/liebiao/202308/content_6901312.htm. (In Chinese)

[4] Keough J R. Austempered ductile iron (ADI) – A green alternative. Applied Process Inc. Technologies Div. – Livonia, April 2010, Michigan, USA.

[5] Liu J C. Unique microstructure and excellent mechanical properties of ADI. China Foundry, 2006, 3(4): 253–257.

[6] Stefanescu D M. The Meritocratic ascendance of cast iron: From magic to virtual cast iron. International Journal of Metalcasting, 2019, 13(4): 726–752.

[7] SolarFeeds Marketplace. Solar tracker reviews: Cost, types, advantages. https://www.solarfeeds.com/mag/wiki/solar-tracker, updated on September 4, 2019.

[8] Jenks2026. Solar tracking systems: Maximizing energy production. https://green.org/2024/01/30/solar-tracking-systems-maximizing-energy-production, January 30, 2024.

[9] Bailey E. Types of solar tracking system: A comprehensive guide to optimal energy harvesting. https://solvoltaics.com/types-of-solar-tracking-system, August 28, 2023.

[10] Seme S, Stumberger B, Hadziselimovic M, et al. Solar photovoltaic tracking systems for electricity generation: A review. Energies, 2020, 13(16): 1–24.

[11] Baouche F Z, Abderezzak B, Ladmi A, et al. Design and simulation of a solar tracking system for PV. Appl. Sci., 2022, 12(19): 9682. https://doi.org/10.3390/app12199682.

[12] Yang Z H, Xiao Z Q. Review of the sustainable development of solar photovoltaic tracking system technology. Energies, 2023, 16(23): 7768. https://doi.org/10.3390/en16237768.

[13] Lu Y X and Lu Q H. Development of ADI top plate in solar PV power. In: Proc. 2017 Forum on Melting and Treatment Technology of High-end Iron Castings and The 6th National ADI Technology Seminar, Zhengzhou China, June 28–30, 2017.

[14] Lohmiller J, Hoffmeister J, Hermes J, et al. Development and investigation of austempered ductile iron (ADI) for thick-walled gear components. Engineering Research, 2017, 81: 253–263. https://doi.org/10.1007/s10010-017-0238-9.

[15] Weber F, Broeckmann C, Züch V, et al. Multi-domain optimization of cast iron components in wind turbines. Engineering Research, 2023, 87: 39–50. https://doi.org/10.1007/s10010-023-00616-3.

[16] Keough J R and Popovski V M. Large austempered parts – monster opportunities. AFS Conference, April 19, 2012.

[17] Proctor D. Siemens Gamesa reportedly developing 21-MW offshore wind turbine. https://www.powermag.com/siemens-gamesa-reportedly-developing-21-mw-offshore-wind-turbine/, June 11, 2024.

[18] Paakkinen P, Soivio K, Uusitalo K. Thick walled ADI castings to boost torque density of wind turbine gearboxes. Moventas Gears Oy., 2018. https://api.semanticscholar.org/CorpusID:199395627.

[19] Li K R, Li Z L, Cui Y, et al. Strengthening technology innovation and promoting high-quality development. In: Proc. Henan Province Annual Conference on Casting and Forging Industries, Zhengzhou, China, July 6–8, 2022. (In Chinese)

[20] Collie B, Xu G, Yu C, et al. Hitting the road: New energy HDTS bright future. https://web-assets.bcg.com/3c/8b/42d2b1dd4560b963a4ff3fbd4024/bcg-hitting-the-road-new-energy-hdts-bright-future-en-20230614.pdf, June 2023.

[21] Els P. Fueling the future of the internal combustion engine. https://insights.globalspec.com/article/18413/fueling-the-future-of-the-internal-combustion-engine.

[22] Li T, Heng L Q, You D F, et al. Application of ADI for suspension components in off-road vehicles. In: Proc. 2016 World Conference on Austempered Ductile Iron, Atlanta, GA, USA, October 27–28, 2016.

[23] The top 10 rankings of heavy, medium, light and micro cards in the "Year-end Exam" of 2023 have been announced. https://www.sohu.com/a/751417730_121749385. (In Chinese)