Supplementary Materials for

The Perfect Alliance: How Regulation and Technology Converge to Drive the Implementation of Minamata Convention

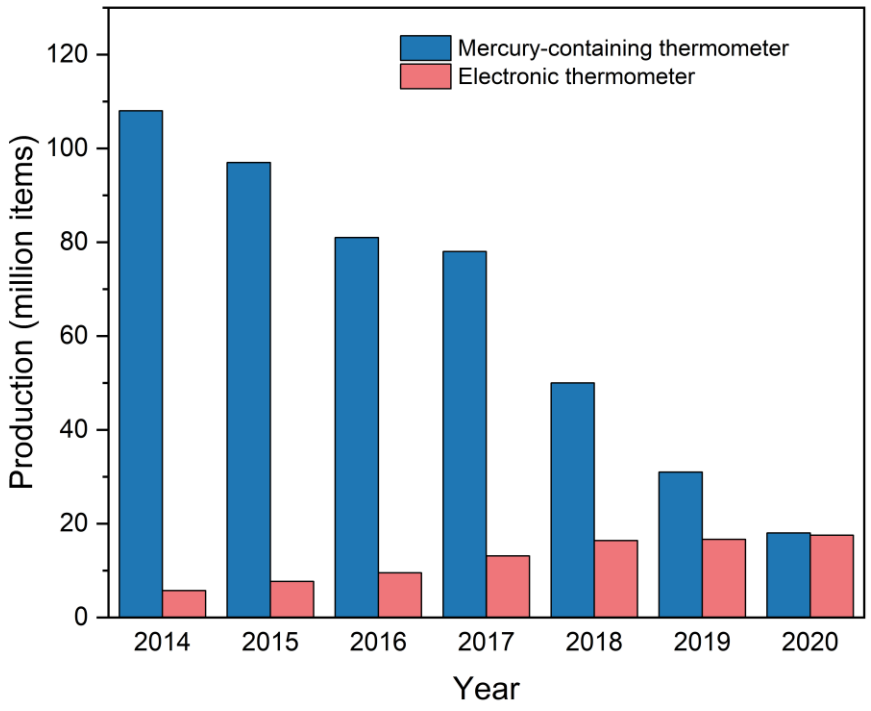


Fig. S1 Production and mercury content trends in mercury-containing thermometer and electronic thermometer

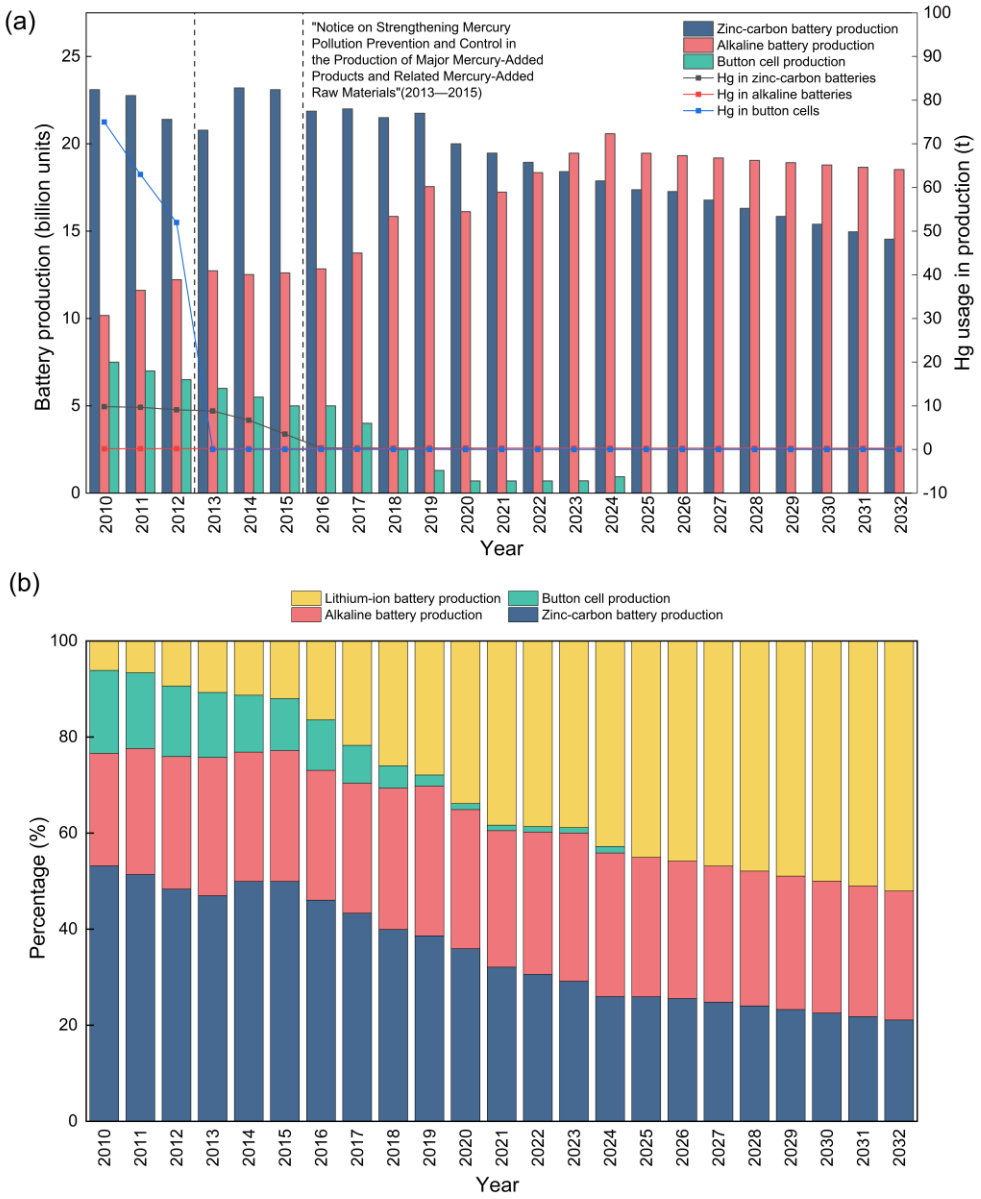


Fig. S2 (a) Production and mercury content trends in mercury-containing battery (2010-2032); (b) Production share of different battery types in China (2010-2024)

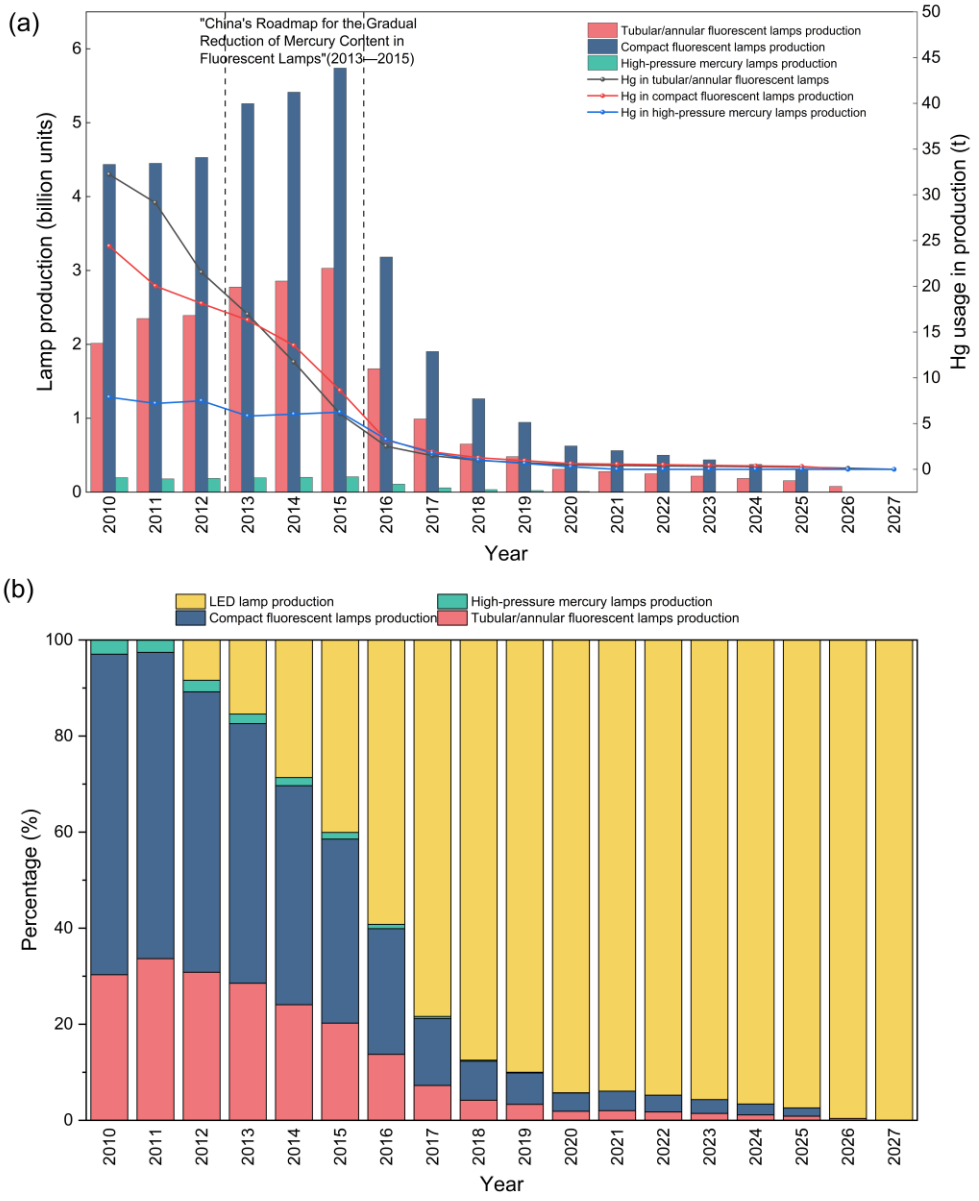


Fig. S3 (a) Production and mercury content trends in mercury-containing lamps (2010-2027); (b) Production share of different lamps types in China (2010-2024)

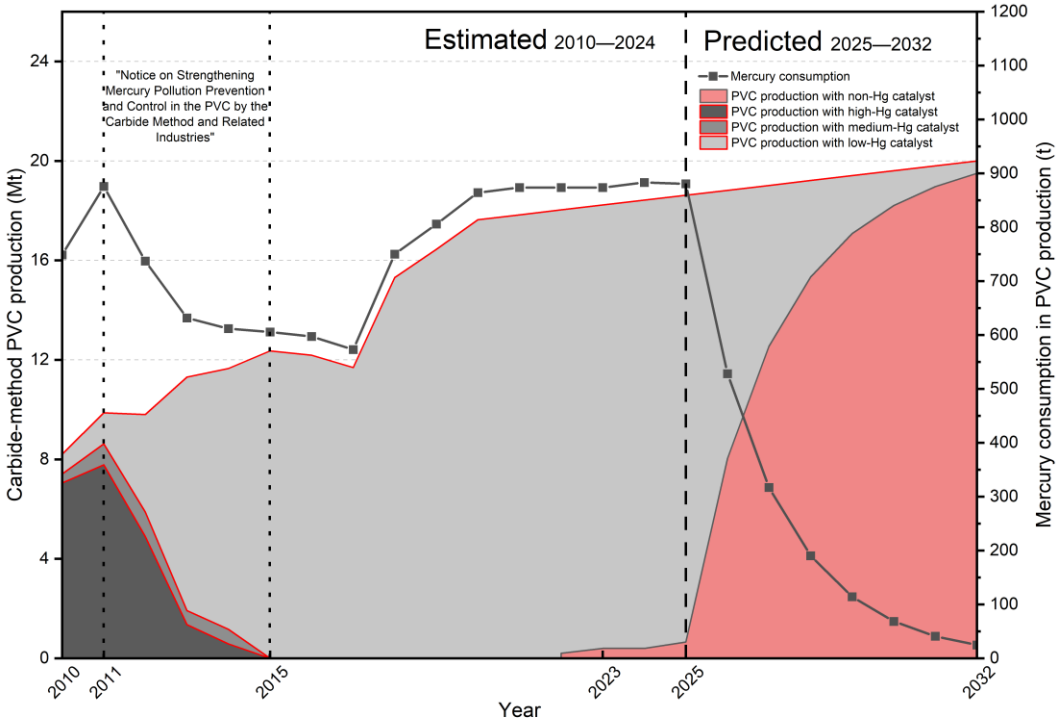


Fig. S4 The trend of calcium carbide method PVC production and mercury usage changes

Table S1. Timeline of mercury reduction policies for batteries in China

Year	Policy Title	Main Content
1997	*Regulations on Limiting Mercury Content in Battery Products*	1. Production of batteries with mercury content > 0.025% was scheduled to stop in 2001, with sales banned starting 2002. 2. Production of batteries with mercury content > 0.0001% (mercuric oxide button cells) was scheduled to stop in 2005, with sales banned starting 2006.
2003	*Technical Policy on Pollution Prevention of Waste Batteries*	In 2003, the production and sale of mercury oxide batteries were banned.
2009	*Requirements on the Limitation of Mercury, Cadmium and Lead for Mercury and Non-mercury Zinc-Manganese Dioxide Batteries* GB 24427-2009	Set mercury content standards.
2009	*Requirements on the Limitation of Mercury Content for Zinc-Silver Oxide, Zinc-Air, and Zinc-Manganese Dioxide Batteries* GB 24428-2009	Set mercury content standards.
2012	*12th Five-Year Plan for Industrial Cleaner Production*	Promoted mercury-free technology for button-type alkaline zinc-manganese batteries in the battery industry, achieving 100% technology coverage by 2015.
2013	*Notice on Strengthening Pollution Prevention Work for Major Products and Raw Materials in the Battery Industry*	By 2015, mercury-free zinc-manganese and button batteries were fully achieved.
2017	*Minamata Convention on Mercury Takes Effect*	Banned the use of mercury-containing batteries by 2020.
2021	*Requirements on the Limitation of Mercury Content for*	Non-alkaline zinc-manganese batteries must have mercury content less than 0.001%.

Year	Policy Title	Main Content
	Alkaline Zinc-Manganese Batteries GB 24427-2021	

Table S2. Timeline of mercury reduction policies for lamps in China

Year	Policy Title	Main Content
2008	*Requirements on the Limitation of Hazardous Substances in Lighting Products* QB/T 2008	Mercury content less than 0.1%.
2012	*12th Five-Year Plan for Industrial Cleaner Production*	The lighting (fluorescent lamp) industry promoted mercury reduction. Single fluorescent lamp mercury content reduced to below 2 mg in efficient products. By 2015, 80% of products met the technical requirements.
2013	*China Roadmap for Gradual Reduction of Mercury Content in Fluorescent Lamps*	Gradual mandatory mercury content limits for fluorescent lamps. By the end of 2015, 80% of fluorescent lamps were required to meet mercury limits.
2017	*Minamata Convention on Mercury Takes Effect*	By 2020, the production and import/export of fluorescent lamps exceeding mercury content limits were prohibited.
2019	*Guidance Catalogue for Industrial Structure Adjustment (2019 Edition)*	Supplemented the full scope of public procurement indicators with mercury-containing fluorescent lamps included.

Table S3. Timeline of mercury reduction policies for VCM in China

Year	Policy Title	Main Content
2010	*Notice on Mercury Pollution Prevention and Control in Acetylene-based VCM Industry* MIIT [2010] No. 261	Clearly proposed full promotion of mercury-free catalysts, especially natural gas-based catalysts, and clarified specific objectives and indicators for mercury pollution control.
2011	*Notice on Strengthening Mercury Pollution Control in Acetylene-based VCM Industry* MEE [2011] No. 4	1. By the end of 2015, all existing acetylene-based VCM enterprises must fully adopt mercury-free catalysts. 2. From 60 days after the policy was issued, newly built, rebuilt, or expanded acetylene-based VCM facilities must adopt mercury-free catalysts. 3. High-mercury catalysts must be banned in all enterprises producing VCM with high-mercury catalysts before the deadline.
2012	*12th Five-Year Plan for Cleaner Production – VCM Industry Entry Standards*	Promoted low-mercury and efficient mercury catalyst application in acetylene-based VCM industry. In 2015, targets for full adoption of advanced low-mercury and high-efficiency catalysts were 100% and 60%, respectively.
2015	*Notice on Further Strengthening Mercury Pollution Prevention in VCM Industry*	Promoted adoption of mercury-free catalysts in the VCM sector; required enterprises to strengthen mercury pollution control, promote mercury-free technologies and applications.
2017	*Minamata Convention on Mercury Takes Effect*	VCM production, mercury catalysts, and mercury emissions are included in the scope of control. Required full phase-out of mercury-based catalysts.
2019	*Technical Specification for Pollution Discharge Permit for VCM Industry*	Incorporated catalyst use, mercury discharge, and environmental protection requirements into the permit system.
2022	*Opinions on Further Strengthening Heavy Metal Pollution Prevention*	(1) VCM industry must reduce mercury catalyst use; prohibited construction of new production lines using mercury-based catalysts. (2) Promote mercury-free catalyst technology and equipment in VCM industry.

Data from 2010–2024 represent reported or estimated production volumes based on industrial statistics and market reports for the following products: thermometers, fluorescent lamps, batteries, and vinyl chloride monomer (VCM). This includes production data for thermometers (Lin et al., 2016; Wind database, 2025), fluorescent lamps (China Light Industry Yearbook Editorial Office, 2021), batteries (Lin et al., 2020; Wang et al., 2025), and VCM(Lin et al., 2016). For years where reported data were unavailable due to practical constraints, missing values were filled using interpolation methods to ensure temporal continuity of the data set. Values for 2025 onwards are projections derived from sector-specific growth rates, assuming a steady annual increase in production consistent with historical trends. For VCM production, the projections incorporate mercury recovery practices: since approximately 60% of mercury used in the carbide-based VCM industry is collected and recycled during production, the net intentional mercury consumption was estimated by applying a 60% annual reduction factor to mercury use. This approach reflects both the gradual phase-out requirements of the Minamata Convention and the expected technological improvements in mercury recovery and catalyst substitution. Consequently, the post-2025 values should be interpreted as indicative pathways under a regulated transition scenario rather than as precise forecasts.

Table S4. Descriptions of codes

CODE	Description
TM	Medical thermometer
FT	Tabular + ring fluorescent lamp
CFL	Compact fluorescent
HID	High-intensity discharge lamp
LED	Light Emitting Diode lamp
CellC1	Zinc–carbon battery
CellC2	Alkaline–manganese battery
CellB	Button battery
CellLi	Lithium Battery
VCM_H	High-mercury catalyst based VCM production
VCM_M	Medium-mercury catalyst based VCM production
VCM_L	Low-mercury catalyst based VCM production
VCM_N	Non-mercury catalyst based VCM production

Table S5. Production volume of all the products from 2010—2020

YEAR	TM items	FT items	CFL items	HID items	LED items
2010	150316000	2014000000	4435000000	197000000	-
2011	152000000	2349000000	4450000000	180000000	-
2012	152000000	2390719691	4529034749	187000000	650000000
2013	120000000	2775266409	5257528958	194000000	1500000000
2014	108000000	2856891892	5412162162	201000000	3400000000
2015	97000000	3029212355	5738610039	208000000	6000000000
2016	81000000	1669606178	3181805020	108500000	7200000000
2017	78000000	989803089	1903402510	58750000	10700000000
2018	50000000	649901544	1264201255	33875000	13600000000
2019	31000000	479950772	944600627	21437500	13000000000
2020	18000000	310000000	625000000	9000000	15500000000
2021	16200000	279000000	562500000	0	13000000000
2022	14400000	248000000	500000000	0	13500000000
2023	12600000	217000000	437500000	0	14500000000
2024	10800000	186000000	375000000	0	15950000000
2025	9000000	155000000	312500000	0	17545000000
2026	7200000	77500000	0	0	19299500000
2027	5400000	0	0	0	-
2028	3600000	0	0	0	-
2029	1800000	0	0	0	-
2030	0	0	0	0	-
2031	0	0	0	0	-
2032	0	0	0	0	-

Table S5 Continued

YEAR	CellC1 items	CellC2 items	CellB items	CellLi items
2010	23100000000	10175000000	7500000000	2660000000
2011	22760000000	11615000000	7000000000	2930000000
2012	21400000000	12220000000	6500000000	4160000000
2013	20780000000	12730000000	6000000000	4740000000
2014	23200000000	12515000000	5500000000	5250000000
2015	23100000000	12610000000	5000000000	5550000000
2016	21870000000	12840000000	5000000000	7800000000
2017	22000000000	13750000000	4000000000	11040000000
2018	21500000000	15845000000	2500000000	13987000000
2019	21750000000	17550000000	1300000000	15720000000
2020	20000000000	16120000000	700000000	18845000000
2021	19469250000	17235000000	700000000	23260000000
2022	18938500000	18350000000	700000000	23930000000
2023	18407750000	19465000000	710000000	24528000000
2024	17877000000	20580000000	940000000	29457000000
2025	17769738000	19460000000	940000000	30193425000
2026	17663119572	19323780000	0	30948260625
2027	17557140855	19188513540	0	31721967141
2028	17451798009	19054193945	0	32515016319
2029	17347087221	18920814588	0	33327891727
2030	17243004698	18788368885	0	34161089020
2031	17139546670	18656850303	0	35015116246
2032	17036709390	18526252351	0	35890494152

Table S5 Continued

YEAR	VCM_H	VCM_M	VCM_L	VCM_N
	tons	tons	tons	tons
2010	7049455	363679	796317	0
2011	7781894	837018	1251578	0
2012	4900324	980065	3920259	0
2013	1356804	565335	9384561	0
2014	582750	582750	10489500	0
2015	0	0	12358000	0
2016	0	0	12191000	0
2017	0	0	11690000	0
2018	0	0	15306832	0
2019	0	0	16443947	0
2020	0	0	17635222	0
2021	0	0	17682863	0
2022	0	0	17346384	400000
2023	0	0	17431078	400000
2024	0	0	16692300	800000
2025	0	0	16492300	1000000
2026	0	0	9895380	7596920
2027	0	0	5937228	11555072
2028	0	0	3562337	13929963
2029	0	0	2137402	15354898
2030	0	0	1282441	16209859
2031	0	0	769465	16722835
2032	0	0	461679	17030621

In regions where ethylene access remains limited, mercury-free catalysts are currently employed and have been demonstrated to be both technically and economically viable, as evidenced by published news reports and related website postings from three facilities. For instance, the Environmental Impact Report for a mercury-free VCM production line (10000 tons capacity) at Zhongtai Chemical Co., Ltd. indicates that substituting low-mercury catalysts with mercury-free alternatives reduces heavy metal mercury emissions and decreases wastewater treatment costs, with a total investment return rate of 18.51%, reflecting robust profitability. The Minamata Convention stipulates that once the Conference of the Parties confirms the technical and economic feasibility of mercury-free catalyst technology based on existing processes, the use of mercury shall be prohibited after a five-year period. In the calcium carbide-based PVC production process, approximately 60% of mercury is recovered from spent mercury catalysts. Consequently, to proactively adapt to mercury-free production, it is projected that all mercury used in China's PVC production will originate from recycling in the future. Under the assumption of constant PVC output, mercury consumption is expected to decline at an annual rate of 40%, with the remaining production compensated by mercury-free methods. Looking ahead, a full transition to mercury-free production is projected. From 2025 onwards, the share of non-mercury catalyst-based PVC production is expected to expand rapidly, while the use of low-mercury catalysts declines. By 2032, mercury consumption is anticipated to be reduced to 3% of its 2010 level. This projection is grounded in multiple structural shifts: first, China's ethylene production capacity is projected to increase by 80% by 2030, driving a significant expansion of ethylene-based PVC production. As a result, although total PVC output is expected to nearly double by 2032, the share of carbide-method PVC is projected to decline from 80% in 2024 to 60% in 2032. Second, due to the nearly complete mercury catalyst recovery achieved in China's PVC production, with approximately 60% of mercury in spent catalysts being recyclable, the projected mercury consumption after 2025 is assumed to decline annually at a rate of 60%. The remaining PVC production demand will be fully met by adopting non-mercury catalyst technologies, which are expected to become increasingly widespread as technological innovation and regulatory measures progress. This assumption reflects both the high recovery efficiency of mercury catalysts and the accelerating transition of the PVC industry toward mercury-free production pathways. This assumption reflects both the high recovery efficiency of mercury catalysts and the accelerating transition of the PVC industry toward mercury-free production pathways. By 2032, mercury-based carbide PVC processes are projected to account for only about 5% of total production.

Two fundamental assumptions were adopted: (1) China's total PVC production would remain constant at the baseline level after 2025; (2) The production capacity of VCM_L would decline at an annual rate of 40% starting in 2026.

To maintain constant total production, the phase-out of VCM_L capacity would be entirely compensated for by the increase in VCM_N capacity. The production for year was calculated using the following formulas:

$$VCM_L_i = VCM_L_{i-1} * 60\%$$

$$VCM_N_i = VCM_L_{i-1} + VCM_N_{i-1} - VCM_L_i$$

Where VCM_L_i signifies the production output of the low-mercury catalyst process in year i measured in tonnes; and VCM_N_i indicates the corresponding output of the mercury-free catalyst process.

Table S6. Technical facts of Hg containing products

YEAR	TM	FT	CFL	HID	CellC1	CellC2	CellB
	g Hg/item	mg Hg/item	mg Hg/item	mg Hg/item	mg/item	mg/item	mg/item
2010	1	16	5.5	40	0.425	0.016	10
2011	1	12.4	4.5	40	0.425	0.016	9
2012	1	9	4	40	0.425	0.016	8
2013	1	6.1	3.1	30	0.425	0.016	0.005
2014	1	4.1	2.5	30	0.289	0.016	0.005
2015	1	2	1.5	30	0.153	0.016	0.005
2016	1	1.5	1	30	0.016	0.016	0.005
2017	1	1.5	1	30	0.016	0.016	0.005
2018	1	1.5	1	30	0.016	0.016	0.005
2019	1	1.5	1	30	0.016	0.016	0.005
2020	1	1.5	1	30	0.016	0.016	0.005
2021	1	1.5	1	0	0.016	0.016	0.005
2022	1	1.5	1	0	0.016	0.016	0.005
2023	1	1.5	1	0	0.016	0.016	0.005
2024	1	1.5	1	0	0.016	0.016	0.005
2025	1	1.5	1	0	0.016	0.016	0.005
2026	1	1.5	0	0	0.016	0.016	0
2027	1	1.5	0	0	0.016	0.016	0
2028	1	0	0	0	0.016	0.016	0
2029	1	0	0	0	0.016	0.016	0
2030	1	0	0	0	0.016	0.016	0
2031	0	0	0	0	0.016	0.016	0
2032	0	0	0	0	0.016	0.016	0

Table S7. Technical facts of Hg containing catalyst

	High Hg catalyst	Middle Hg catalyst*	Low Hg catalyst	Mercury-free catalyst**
kg Catalyst/t VCM	1.20	1.20	1.20	2.20
$HgCl_2$ content in catalyst	11.0%	8.0%	5.5%	0%
$HgCl_2$ content range	10%–12%	7%–9%	4.5%–6.5%	0%
$Hg/HgCl_2$	0.74	0.74	0.74	—
g Hg/t VCM produced	97	71	49	0

Note:

* The middle Hg catalyst is a mixture of high and low Hg catalyst. During the transition, some plants used this to exhaust existing stocks and to test process adaptability to lower-Hg content catalysts. The middle Hg catalyst was only used for a few years between 2000 and 2014.

**The mercury-free catalyst uses precious metal (e.g., gold or palladium) or non-metal oxide technologies, and eliminates Hg completely. Catalyst dosage is typically lower, though economic and technical barriers remain.

Supplementary text

Several mercury-free catalyst platforms have been investigated for acetylene hydrochlorination, including copper-based, metal-free carbon-based, ruthenium-based and ionic-liquid systems. Among these, gold-based catalysts are currently the most technologically mature and the only option with demonstrated commercial-scale application. The other catalyst systems remain largely at the laboratory or pilot-testing stage, with no documented full-scale commercial operation; consequently, their costs under sustained industrial-scale conditions cannot yet be reliably quantified. Gold-based catalysts were therefore selected as the commercially validated benchmark for the cost comparison presented here.

The gross catalyst cost per tonne of VCM was estimated as:

$$C_j = \frac{P_j}{Y_j} \quad (1)$$

where C_j is the catalyst cost per tonne of VCM (USD/t VCM), P_j is the reported catalyst price (USD/t catalyst), and Y_j is the cumulative catalyst productivity (t VCM/t catalyst). Here, P_{LM} and C_{LM} denote the reported price of the low-mercury catalyst and its corresponding cost per tonne of VCM, respectively, while P_{Au} and C_{Au} denote the reported price of the gold-based mercury-free catalyst and its corresponding cost per tonne of VCM, respectively. All RMB-denominated values were converted using an exchange rate of RMB 1 = USD 0.15.

For low-mercury catalysts, the reported procurement price of RMB 52000–73500 per tonne of catalyst (CMC International Tendering Co., 2025; Gep Research, 2026) corresponds to:

$P_{\mathrm{LM}} = (52000 - 73500) \times 0.15 = 7800 - 11025$ USD/t catalyst

Using a typical catalyst productivity of approximately 1000 kg VCM per kg catalyst (Johnston et al., 2015), equivalent to 1000 t VCM per tonne of catalyst, the direct catalyst cost was estimated as:

$C_{\mathrm{LM,lower}} = \frac{7800}{1000} = 7.8$ USD/t VCM

$C_{\mathrm{LM,upper}} = \frac{11025}{1000} = 11.0$ USD/t VCM

$C_{\mathrm{LM}} = 7.8 – 11.0$ USD/t VCM

For gold-based mercury-free catalysts, the reported price of RMB 424800 per tonne of catalyst (Xi'an Kaili New Materials Co. and China Securities Co., 2023) corresponds to:

$$P_{\mathrm{Au}} = 424800 \times 0.15 = 63720 \quad \text{USD/t catalyst}$$

Based on a cumulative productivity of approximately 2100–3000 kg VCM per kg catalyst (Johnston et al., 2015), the corresponding cost range is:

$$C_{\mathrm{Au,lower}} = \frac{63720}{3000} = 21.2 \text{ USD/t VCM}$$

$$C_{\mathrm{Au,upper}} = \frac{63720}{2100} = 30.3 \text{ USD/t VCM}$$

$$C_{\mathrm{Au}} = 21.2 - 30.3 \text{ USD/t VCM}$$

Thus, the estimated gross cost of the gold-based mercury-free catalyst is approximately 2.7 times that of the low-mercury catalyst. This result is broadly consistent with an independent comparison showing that mercury-based catalysts account for less than 1% of total PVC production costs, whereas gold-based catalysts account for approximately 2% (Ciriminna et al., 2016).

References

China Light Industry Yearbook Editorial Office (2021). China light industry yearbook 2021. Available online at http://www.tjnjw.com/hangyefb/q/zhongguo-qinggongye-nianjian-2021.html (accessed July 31, 2026)

Ciriminna R, Falletta E, Della Pina C, Teles J H, Pagliaro M (2016). Industrial applications of gold catalysis. *Angewandte Chemie International Edition*, *55*(46): 14211–14217. doi:10.1002/anie.201604656

CMC International Tendering Co. Ltd (2025). Announcement of successful bid candidates for package 4 (catalyst) under the procurement of four auxiliary materials by CNSIG inner mongolia chemical Co., ltd. Tender Award Candidate Announcement. Beijing, China: China General Tendering Network. Available online at https://www.china-tender.com.cn/jghw/66451.jhtml (accessed July 30, 2026)

Gep Research (2026). Global low-mercury catalyst industry chain and value chain analysis report (2026, GEPH6C8Y). Industry Research Report. GEP Research. Available online at https://www.gepresearch.com/77/view-1040712-1.html (accessed July 30, 2026)

Johnston P, Carthey N, Hutchings G J (2015). Discovery, development, and commercialization of gold catalysts for acetylene hydrochlorination. *Journal of the American Chemical Society*, *137*(46): 14548–14557. doi:10.1021/jacs.5b07752

Lin H, Cao K, Cao G (2020). General situation of battery industry in China in 2019. *Battery Industry*, *24*(1): 43–46

Lin Y, Wang S, Wu Q, Larssen T (2016). Material flow for the intentional use of Mercury in China. *Environmental Science & Technology*, *50*(5): 2337–2344. doi:10.1021/acs.est.5b04998

Wang H, Zhang C, Lin H, Huang Q, Song W, Cai J, Ma X, Cao G (2025). Operation condition of the chinese battery industry in 2024. *Battery Bimonthly*, *55*(1): 11–18. doi:10.19535/j.1001-1579.2025.01.002

Wind database (2025). Available online at https://www.wind.com.cn/portal/zh/EDB/index.html (accessed January 1, 2025)

Xi'an Kaili New Materials Co. Ltd, China Securities Co. Ltd (2023). Response of the issuer and sponsor to the first-round review inquiry letter regarding xi'an kaili new materials Co., ltd.'s application for issuance of shares to specific investors (revised version). Regulatory Filing. Xi'an, China: Xi'an Kaili New Materials Co., Ltd.; China Securities Co., Ltd. Available online at https://file.finance.sina.com.cn/211.154.219.97:9494/MRGG/CNSESH_STOCK/2023/2023-12/2023-12-14/9708689.PDF (accessed July 30, 2026)