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Assessing Aspects of Cadmium Supply, Recycling and Environmental Pollution with Respect to Future Photovoltaic Technology Demands and Environmental Policy Goals

Harald Ulrik Sverdrup · Ole van Allen · Hördur Valdimar Haraldsson

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Abstract Cadmium has appeared as an important element for certain types of solar cells and rechargeable batteries. It is possible that there will be a large increase in demand for technical cadmium in the future. This is in conflict with environmental policies for phasing out cadmium from any technical use worldwide because of its great toxicity to humans. Cadmium toxicity is on par with that of mercury, and data suggests that cadmium exposure has no safe lower limit. There is no shortage of cadmium to extract, and no shortage from lack of cadmium available in the future zinc flow is to be expected. There is a global treaty to ban it from all use. The Integrated Assessment Model WORLD7 was used to assess different aspects of the supply of cadmium to society. It would be possible to produce at least 250,000 tons/year; in reality, the 2023 production is about 24,000 tons/year. The price is about 3500–4500 $/ton and is volatile. Because there is a United Nations agreed global policy to phase out cadmium from all use, demand for cadmium will soon not be met, and there will be an actual shortage of cadmium for any use, including photovoltaic technologies and semiconductors. This is good news for nature, but bad news for the CdTe and CIGS types of photovoltaic panels. It is estimated that only 25% of the planned future capacity may not be available unless good substitutes for cadmium can be found.

Keywords WORLD7 · Cadmium · Sustainability · Photovoltaics · Environmental pollution · Cadmium Toxicity

H. U. Sverdrup (✉) · O. van Allen
System Dynamics, Gameschool, Inland Norway University of Applied Sciences, Holsetgaten 31, NO-2315 Hamar, Norway
e-mail: harald.sverdrup@inn.no

O. van Allen
e-mail: ole.allen@inn.no

H. V. Haraldsson
European Environmental Agency, Kongens Nytorv 6, 1050 Copenhagen, Denmark
e-mail: hordur.haraldsson@eea.europa.eu

1 Introduction

Cadmium, a very toxic element, is on the way to being phased out of all global use, according to the UN/ECE-LRTAP (UN/ECE, 1998). Cadmium use is banned by the UN globally at present. It can only be used as long as full recovery can be secured under special permission (Bakker et al., 1998; de Vries et al., 1998a, 1998b; Sverdrup, 2001; Sverdrup & Ashmore, 2001; van der Voet et al., 2013). It is considered to be of great importance for human health and environmental impacts that cadmium is phased out of all use in human society. The UN/ECE heavy metals protocol was long in preparation and took about 10 years to develop (1988–1998) and 25 years from first beginning to final implementation

(1988–2013). A global ban was not agreed until 2015 and was not implemented until after 2020 (UN/ECE-LRTAP 1998, Balali-Mood et al., 2021).

Cadmium has appeared as an important element for certain types of solar cells and rechargeable batteries. New technologies for solar panels use cadmium in small amounts, such as the cadmium-tellurium technology (CdTe), and can also occur in the CIGS type of solar panel. Bleiwas (2010) explains the basics of this technology for cadmium, as well as gallium, germanium, indium, tellurium and selenium, which also are used in this technology (International Cadmium Association, 2019, Öhrlund, 2011; Halada et al., 2008; Marwede & Reller, 2014). In the future, a significant part of global energy production should come from renewable sources to avoid major climate change problems (Gordon et al., 2006; Grandell & Höök, 2015; Halada et al., 2008; Moss et al., 2011; Nassar et al., 2015; Elshkaki & Graedel, 2013; Fthenakis et al., 2009; Zuser & Rechenbeger, 2011). This is assumed to be achieved by using a large number of solar photovoltaic panels and wind energy, as well as much more efficient technologies helping to reduce energy use. In the available policy plans, there is planned a large capacity coming from the use of photovoltaic technologies. Earlier research has indicated (Sverdrup & Ragnarsdottir, 2014; Sverdrup et al., 2024) that the amounts of some of the key materials may come in limited supply (silver, indium, germanium, gallium and tellurium), limiting the installed capacity for a certain technology (Sverdrup et al., 2024). Based on silver, gallium and indium, it appears that about 23% of the demand may be covered with the available material. Thus, careful optimization may be needed to have as much capacity as possible, looking at a system using all technologies exploiting that they have different material demands.

The implication is that there is an increasing demand for cadmium for use in some types of thin-film solar cells. This exposes a goal conflict between phasing cadmium out of society because of its great toxicity to humans and the use of cadmium to generate much-demanded electricity by harvesting solar power. In the past, cadmium was used for permanent colours like yellow and red colours (now forbidden), for electroplating (now forbidden), in dental amalgam (now forbidden), in low-meting point soldering alloys (now forbidden), as stabilisers and chemical additive in polymers and in some industrial processes (being phased out), in photocells, light sensors (looking for alternatives on-going) and nickel–cadmium rechargeable batteries (being phased out).

Figure 1 shows the cadmium production and market price in 1900–2022 and data from USGS 2019, pieced together from various other websites accessed by the authors. Cadmium production peaked in 2018 (Sverdrup & Ragnarsdottir, 2014; see Fig. 1) and is expected to decline to a very low level by 2030 according to the UN/ECE-LRTAP protocol (UN/ECE, 1998). If cadmium production has peaked remains to be verified, but that should be the result of respecting the UN/ECE-LRTAP Århus 1988 Heavy

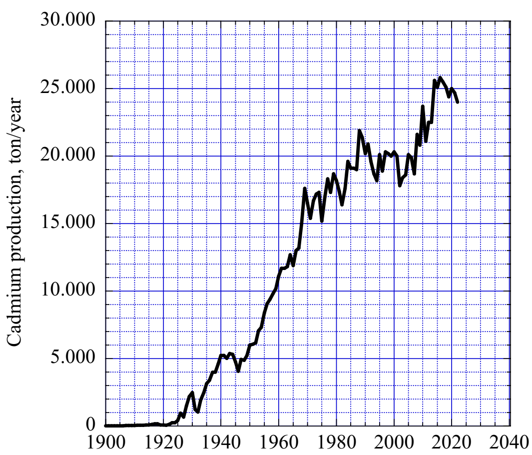


Fig. 1 Cadmium production and market price in 1900–2022. Data from USGS Mineral commodity Summaries from 1993 to 2023 and the ds140 programme. The graphs were made from data pieced together from the USGS archives and various other websites accessed by the authors

Metals Protocol, ratified in 2013 and implemented after 2020. The price has dropped in the later years, possibly because of the collapse of demand for cadmium and the policy of phasing cadmium out from all uses globally.

2 Objectives and Scope

The first goal was to develop an integrated dynamic model for the global market for cadmium as a part of building a long-term supply assessment tool for technology metals required for new energy transition technologies. The WORLD7 model was used to simulate mother metal production rates of copper, zinc and lead (Sverdrup et al., 2017b, 2021). The cadmium sub-model will be validated and embedded inside the WORLD7 model using data for extraction and market price. It will be ensured that it can reconstruct the past with respect to extraction, recycling, supply and market price. In a second step, the WORLD7 model with cadmium will be used to assess the long-term risk for soft or hard scarcity with respect to important new technologies such as thin-film photovoltaic technologies and rechargeable batteries. The effect of having conflicting goals for the fate of cadmium and its use will be investigated.

3 Methods and Theory Used

3.1 Modelling

The main tool employed here is system dynamics modelling. For the modelling, we use the standard methods of systems analysis. We analyse the system using stock-and-flow charts and causal loop diagrams. The mass balance expressed differential equations resulting from the flow charts and the causal loop diagrams were numerically solved using the STELLA® Architect modelling environment (Meadows et al., 1974; Senge, 1990; Sverdrup et al., 2022). We use causal loop diagrams for mapping out where the causalities are, to find intervention points in the system and to propose policy interventions. This method gives more detail, demands more insight and can include more factors including recycling rates and pricing. The Integrated Assessment Model WORLD7 was used for this study (Sverdrup & Olafsdottir, 2019). The reserves and resource estimates for the source metals are based on geological estimates, the interpretation of geological data and the allocation of extractable amounts according to ore quality, stratified with extraction costs (Mudd et al., 2014; Sverdrup & Olafsdottir, 2019; Sverdrup & Ragnarsdottir, 2014; Sverdrup & Olafsdottir, 2019; Krautkraemer, 1988).

The WORLD7 model addresses a large number of metals, and they are all in some way linked in their extraction. The WORLD7 energy module supplies energy from fossil fuels, renewables and nuclear power, with a market price generated by supply and demand in the model. For cadmium, the price has an effect on demand, but not any significant impact on the supply, as this is dependent on the source metal extraction rate. All modules are interconnected. Figure 4 shows the flow chart for the sub-model inside the WORLD7 model dealing with cadmium, with the parent ores and the dependent secondary extraction of many technology metals. The price affects demand, but it does not have any significant impact on the supply, as this is dependent on the mother metal extraction rate. The model as a simple causal loop diagram for the system is shown in Fig. 5. The mining rate is driven by profit from operations. The price is determined by how much metal is available in the market in the same way as in earlier models (Sverdrup & Ragnarsdottir, 2014; Sverdrup et al., 2017b; Sverdrup & Olafsdottir, 2019). A high metal price will increase profits, promote a larger supply to the market and limit demand. More supply to the market will increase the amount available and lower the price.

We have made one important assumption for the business-as-usual scenario for the assessment of future cadmium supply. It was assumed that the use of cadmium for photovoltaic solar panels will be permitted and exempt from the internationally agreed ban under the UN/ECE-LRTAP convention. We have assumed this will be politically justified by the great need for photovoltaic energy and made contingent on reaching a certain level of recycling. If this does not occur, then the assessment will show how fast cadmium will disappear from use in society.

3.2 Resource Estimations

Cadmium is found mostly in zinc ores, lead–zinc ores and multi-metal Ca-Zn-Pb ores, where it is mostly found in the sphalerite mineral, a zinc sulphide

(Frenzel et al., 2016; Wellmer et al., 1990; Zhucheng et al., 2007). Cadmium is found in trace amounts in some iron ores and in some phosphate deposits (USGS, 2022). Phosphate is an important part of industrial fertilisers and, through this, an important pathway to human exposure. Further literature was consulted for numbers (Kelly & Matos, 2014; Brown et al., 2015; Idoine et al., 2022).

The estimation of cadmium resources is problematic (Mudd & Weng, 2012; Mudd et al., 2017; Papp et al., 2008). There are no cadmium mines and thus no dedicated cadmium mining industry. Cadmium is extracted as a by-product of zinc refining, a few copper ores and from recycling (Table 1). In this study, some key assumptions were made: (1) Cadmium is only extractable in mother metals from primary mining. (2) Recycled mother metals have very little content of cadmium. (3) Cadmium is only available if the ore is hydrometallurgical processed and very little technology metals come out with heap leaching methods. Only a few studies make detailed studies of the available resources cadmium; Plachy (2009) and the Mineral Commodities Summaries of the USGS (USGS 2015–2022). The supply security of cadmium depends on source ores for copper and zinc. There is no earlier process-oriented systems dynamics model for cadmium available (Busch et al., 2014; Elshkaki & Graedel, 2013, 2015; Goe & Gustard, 2014; USGS, 2022).

Extraction cut-off is dependent on technology and the degree of repetitiveness of the extraction method (Krautkraemer, 1988; Singer, 1993, 2007). It is composed of different elements: (1) access yield Y_A is the part of the deposits that will be available for this kind of extraction. Some deposits lack physical or legal access and have a composition that prevents extraction. (2) The secondary extraction yield is for when the primary extraction operation does not have the infrastructure to extract the technology metal when the operation is running (Y_S). The secondary yield is the fraction of the potential in the source metals that will be extracted. Some methods, such as heap leaching do not readily give such a secondary substrate. (3) The refining yield is the fraction of the metal recovered from the refining substrate (Y_R). The beneficiation yield is sometimes linked to the cut-off. The extraction cut-off is dependent on technology, extraction costs and the metal price at the time.

$$Y_B = \left(X_O - X_{CO}\right)/X_O$$

where X_O is the ore content, X_{CO} is the ore content that is not captured, the cut-off, and Y_B is the beneficiation yield. For example, if the ore grade is 1.44%, the cut-off is at 0.5%, then the beneficiation yield Y_B has a value of 0.67. If the cut-off is 0.3%, then Y_B=0.79. The refining yield will be a function of the extractive efficiency when treating the ore shipped to the refinery. The material contained below the cut-off grade is lost with the waste. The extractable amount depends on the difference between the ore grade and the refining cut-off grade. It is necessary to account for limited access, the right kind of extraction method, if the infrastructure is available, if the ore allows for it to be extracted and the extraction yield. The total yield is thus

$$Y = Y_A * Y_S * Y_B * Y_R$$

This formula is applied in Table 1 and 2. Table 1 shows the recoverable resources of source metals

Table 1 Cadmium resource estimate using source metal resources and contents in zinc used for cadmium extraction

Source	1850 million ton	2020 million ton	% of mother metal	Content, ton	Y_A %	Y_S %	Y_B %	Y_R %	Y %	Extractable, ton
Zn rich	119	19	2,00	380,000	*70*	*80*	*80*	90	40	152,000
Zn high	350	250	1.44	3,600,000	*70*	*80*	*80*	90	40	1,440,000
Zn low	991	791	1.20	9,492,000	*70*	*80*	*80*	90	40	3,797,000
Zn, ultra	1205	1105	0.60	6,630,000	*70*	*80*	*80*	90	40	4,177,000
Zn sum	2665	2165	0.92	20,102,000					40	8,040,000
Cu	4020	2900	0.002	145,000	60	*80*	*80*	90	54	78,000
Pb	3200	2600	0.003	78,000	60	*80*	*80*	90	54	40,000
Sum				20,247,000					40	8,158,000

Y is the total yield, Y_A is the access and mining yield, and Y_R is the refining yield

Table 2 Cadmium production estimate using source metal resources and contents (Feddersen & Lee, 1954)

Mother metal	Mining rate	Cd content in ore		Cadmium potential, average content and range		Y	Extract. potential	Extracted real
	mill. ton/year	%	ppm	ton/year		%	ton/year	ton/year
Zn	14	0.6–1.44	9300	130,250	132,000–202,000	63	81,900	24,000
Cu	22	0.002–0.005	2500	55,000	44,000–110,000	54	29,700	Stopped
Pb	4.5	0.01–0.05	3000	15,750	4500–22,500	55	8660	Stopped
Sum				201,000			120,260	24,000

Cadmium content is copper, which is in general proportional to the zinc content in the ore

in million tons of metal, and this was used as input data to the WORLD7 model (Sverdrup & Olafsdottir, 2019; Sverdrup & Ragnarsdottir, 2014; Sverdrup et al., 2019). In addition, experiences learned from studying corporate reports and scientific literature discussed in the text were reworked into the resource data and the estimates of costs of extraction. Cadmium is not really scarce. Most of the high and low ore grades of zinc have already been mined, and at present, cadmium comes from the low-grade zinc ore with the highest cadmium content. Not very much globally generalizable information is available. For Y_A and Y_S, there is no data; for Y_B, there are a few hints. Thus, the overall yield is a very approximate estimate, most based on the generic mining experiences of the authors; 80% or 90% yield in a single step may sound very good, but since many steps are involved in the pathway from geological deposits to metal in the market, the total yield is 40–50% as can be seen in Table 1. In summary, Table 1 shows that the available zinc resources contain about 20 million tons of cadmium; we can only expect to be able to extract a maximum of about 8 million tons. This is because of limitations in access to substrate, lack of technological installations and limitations in yields that are realistic. The overall yield for zinc in itself is maybe 80%; thus, from the first geological occurrence of metal in the market, the total yield for cadmium is perhaps no more than 32%.

Table 2 shows a simple cadmium production estimate using source metal resources and contents. The global production was about 22,000 tons in 2013 and about 24,000 tons/year in 2022. There is more cadmium in high-grade ores and less in low-grade ores, as cadmium closely follows zinc. The cadmium extraction rate peaked in 2021 and is now in steady decline. The extraction potential is far above the actual extraction, and demand is in decline in all traditional areas of application. The mother metal ore data has been stratified with respect to ore metal content and relative extraction cost (Phillips & Edwards, 1976). Cadmium comes almost exclusively from zinc ores refining residuals, but historically with small contributions from copper and lead refining.

Table 3 shows the cadmium content for how much cadmium is needed for different photovoltaic harvest technologies in the construction phase, as tons of technology metals are used per installed MW photovoltaic panel capacity (Cesaro et al., 2018; Cucchiella et al., 2015). Table 3 is an important input for any photovoltaic panel sustainability assessment. Only the photovoltaic panel types using cadmium have been included in the table. Another important technical use for cadmium is in

Table 3 Photovoltaic panels, ton of material per used installed MW electricity capacity

Technology	CdTe	CIGS $CuInGaSe_2$	DS-SC sensitised dyes	QDSC quantum dot PV
Ni	-	-	0.03500	0.035
Ag	0.025	0.025	0.02500	0.025
Au	-	-	0.00500	-
Co	-	-	0.01000	-
In	0.015	0.035	-	0.005
Ge	-	-	0.00075	-
Ga	-	0.007	-	0.001
Te	0.060	-	-	-
Cd	**0.060**	**0.001**	**0.01200**	**0.010**
Se	-	0.018	-	0.008
Pt/Pd	-	-	0.00020	-
Ru	-	-	0.00020	-
Sn	-	0.0007	0.01000	-

rechargeable batteries. However, these are being slowly phased out, as there are good substitutes.

3.3 Simulation Model Description

The cadmium model is based on differential equations derived from the mass and energy balances of the cadmium system. Figure 2 shows a causal loop diagram for the extraction process. The mining of zinc is driven by its own economic merit, but supplies a waste, the raw material for cadmium extraction. Provided the substrate is available and is suitable, it will be used for extraction as long as it is profitable. Figure 3 shows the market amount to the price diagram used in the simulations. This parameterizes the market amount to price relationship used in the model (Papp et al., 2008; Sverdrup & Olafsdottir, 2019, 2020a, Olafsdottir & Sverdrup 2021, Sverdrup 2019, Sverdrup et al., 2017a, b). Figure 4 shows the flow chart for cadmium in society, and that is represented in the WORLD7 model. Red lines are cadmium transaction losses. This is a graphical representation of the mass balance for cadmium in the metal supply system. In the model, we have worked with five different uses in society. The use of cadmium in plating and colour has traditionally been the two pathways that contributed most to human cadmium exposure in the past. These have also been the first to be phased out because of health concerns.

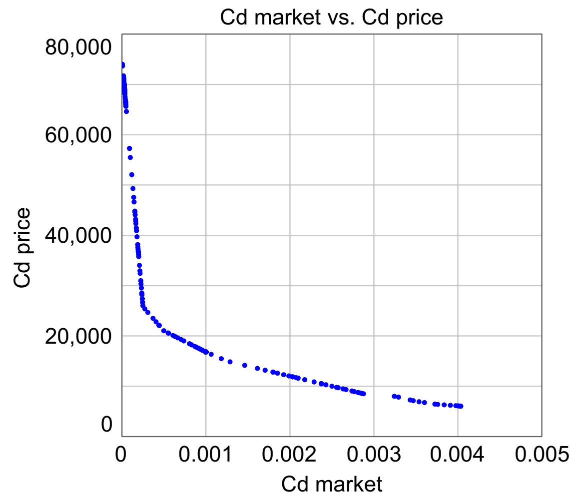


Fig. 3 The market amount to price diagram used in the simulations; see also Sverdrup and Olafsdottir (2019)

Figure 5 shows the causal loop diagram for the cadmium module made for WORLD7. There are three reinforcing loops keeping the system running. They all involve profit and sales and are run by commercial suppliers. The loops marked R1 and R2 run over recapture, recycling and supplies society, and this is shown in blue. Cadmium recapture and recycling have been driven by profit in the past and, more recently, by environmental legislation. The loop marked R3 runs over production from extraction from zinc refining residuals, sales and profits and is marked in red. The loop is driven by commercial profits of the sales of cadmium in the markets. For cadmium, it is necessary to distinguish between recapture and recycling. A steadily growing fraction of the recaptured cadmium will not be recycled, but put into permanent safe storage as a part of removing it from society.

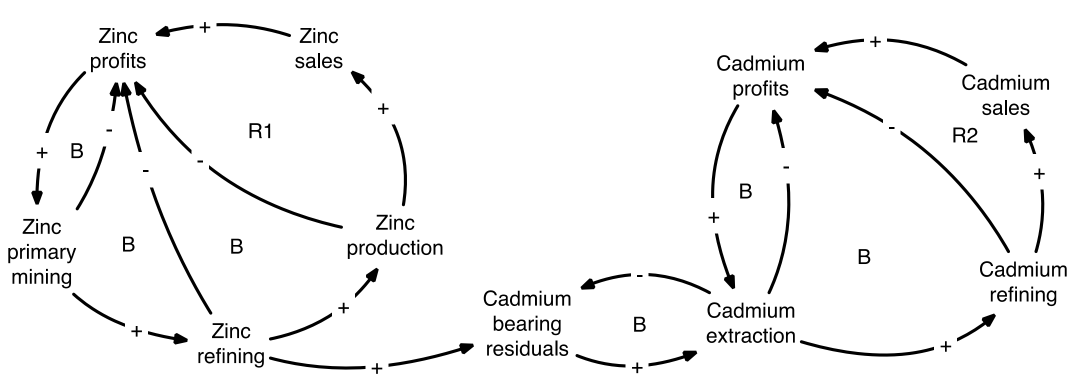


Fig. 2 Causal loop diagram for the extraction process. The mining of zinc is driven by its own economic merit, but supplies a waste, the raw material for cadmium extraction. Provided the substrate is available and suitable, it will be used for extraction as long as it is profitable

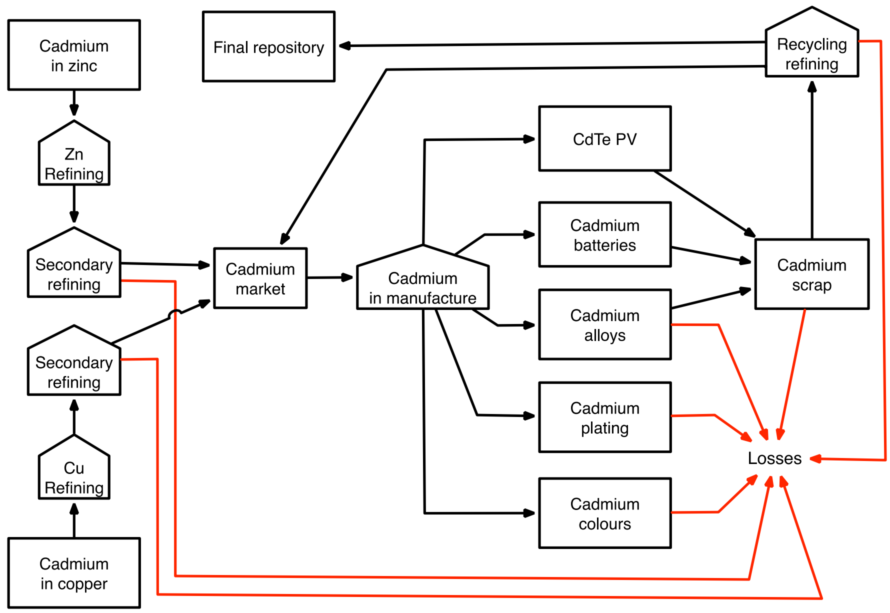


Fig. 4 A flow chart for the flow of cadmium in society, as it is represented in the WORLD7 model. Red lines are losses

Figure 6 shows the cadmium module inside WORLD7 as it was developed for this study. It has three parts: one for handling cadmium in society, one for the market and one for extraction. Figure 7 shows an overview of the whole WORLD7 system, version 7.358 of 1 August 2023. Every red line is one or more causal links. Every box contains one or more system dynamics modules, as specified in the box.

Table 4 shows some aspects of the parameterization of the cadmium sub-model rate coefficients used in the WORLD7 model simulations. The WORLD7 has gone through a number of development stages since 2011; the first version of WORLD7 appeared in 2019 after a major reorganisation of WORLD6 by Olafsdottir and Sverdrup.

4 Results

4.1 The Mother Metal Simulations as Input to the Cadmium Assessment

Figure 8 shows the simulated copper and zinc production using the WORLD7 model. The primary extraction of zinc and copper is the basis for cadmium extraction. The rates do not include recycling nor secondary sources.

4.1.1 The Business-as-usual Simulations for Cadmium

The simulated and observed cadmium production is shown in Fig. 9. In the calculation for cadmium, we have assumed cadmium to be extractable from high-grade and low-grade zinc ores, but it does not occur in extractable amounts and concentrations in ultralow-grade zinc ore. This has to do with the ore genesis process.

Figure 9a shows the simulated demand, modified demand after price feedback, supply, extraction, removed and recycled cadmium. With time, removal replaces recycling as cadmium is phased out. Cadmium is fairly abundant and is produced well below what is possible as measured by occurrence. Cadmium is expected to peak soon, but demand is decreasing for its use as pigment (now 16%) in soldering alloys and in other metal alloys because of health and environmental concerns. Demand is larger than price-modified demand after 1985; this is called soft scarcity. Price-modified demand separates from supply in 2080, and after that, cadmium will be in hard scarcity.

Figure 9b shows the simulated stocks-in-use in different sectors. It can be seen how batteries containing cadmium will be phased out, even if this takes time.

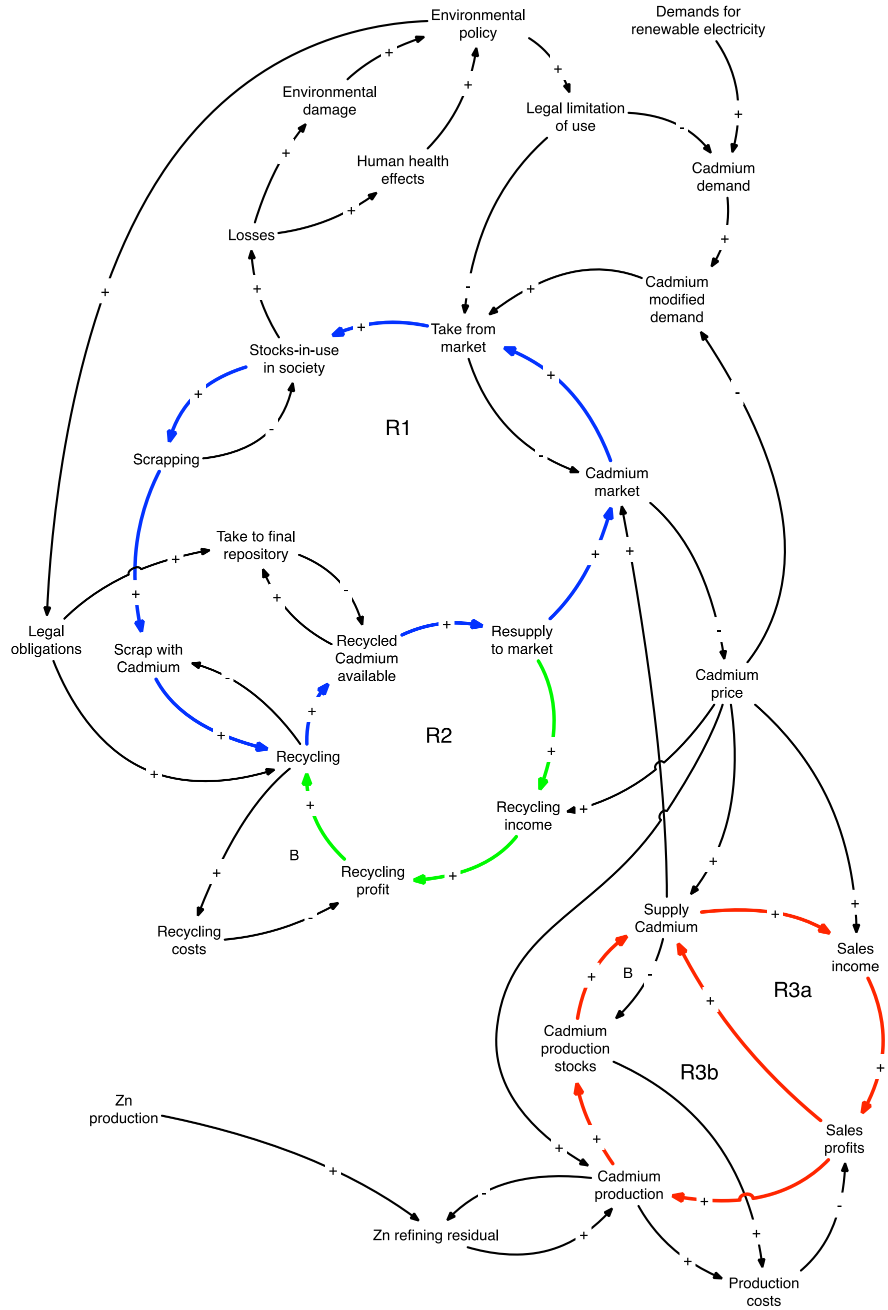


Fig. 5 The causal loop diagram for the cadmium module made for WORLD7. There are three reinforcing loops keeping the system running: R1 runs over recycling and supplies society and is shown in blue; R2 runs over production, sales and profits and is marked in red; and R2 runs over recycling and is marked in red

This is caused by a long lifetime for such batteries and a systemic delay. It can be seen that after 2020, to use of cadmium will be only for photovoltaic technologies. It is estimated that at full planned capacity, some 240,000 tons of cadmium would be required for solar panels alone, which is a substantial amount.

Figure 9c shows the model simulated flow to different cadmium uses. Cadmium use, in general, is at present in decline. Note how the full demand for cadmium to photovoltaic technologies cannot be delivered in the future. This is caused by a limitation to future production capacity and environmental legislation according to international agreements (UN/ECE-LRTAP, 1998).

Figure 9d shows the simulated cadmium flow to colours, plating and alloys as compared to the

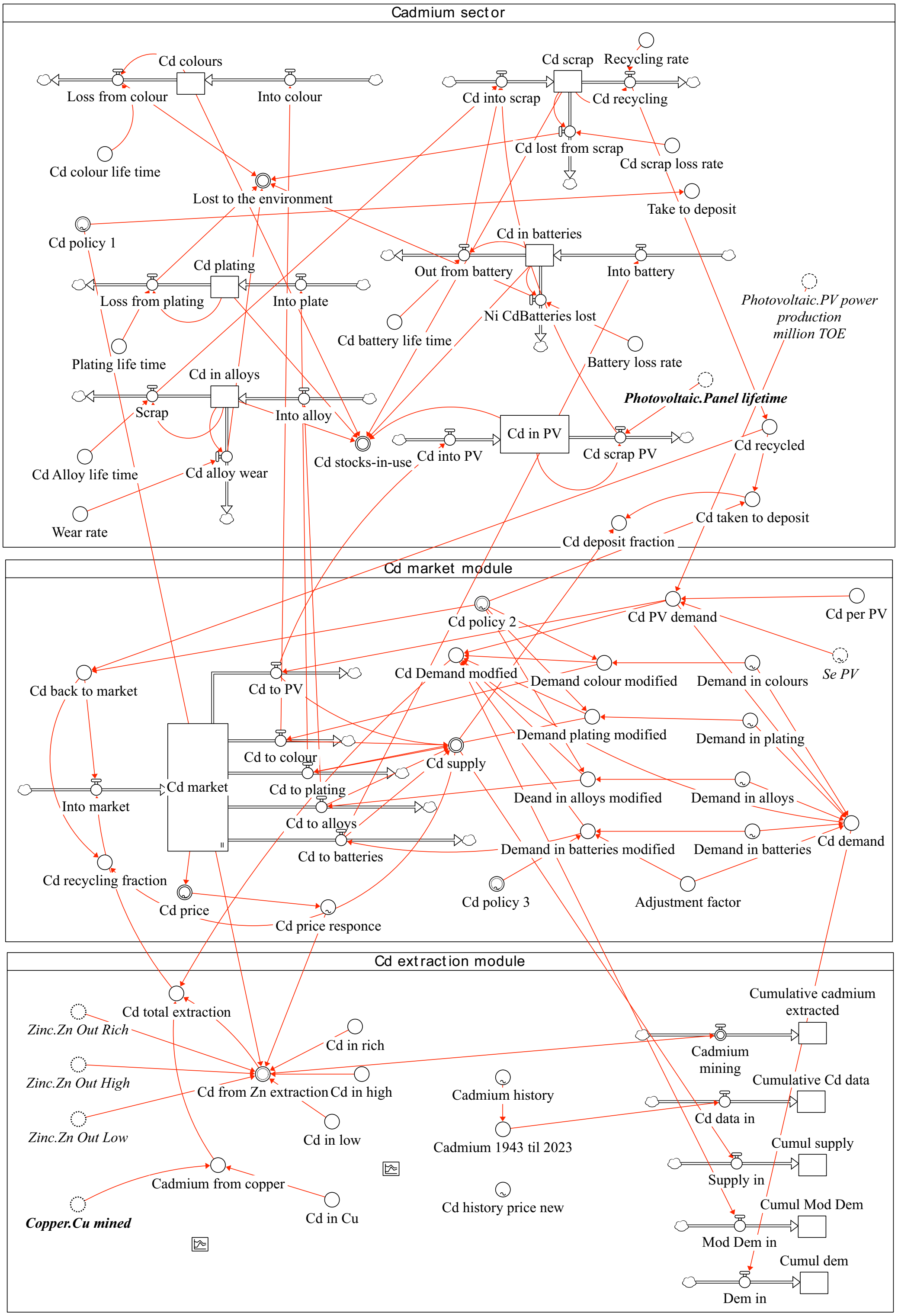


Fig. 6 The cadmium module inside WORLD7

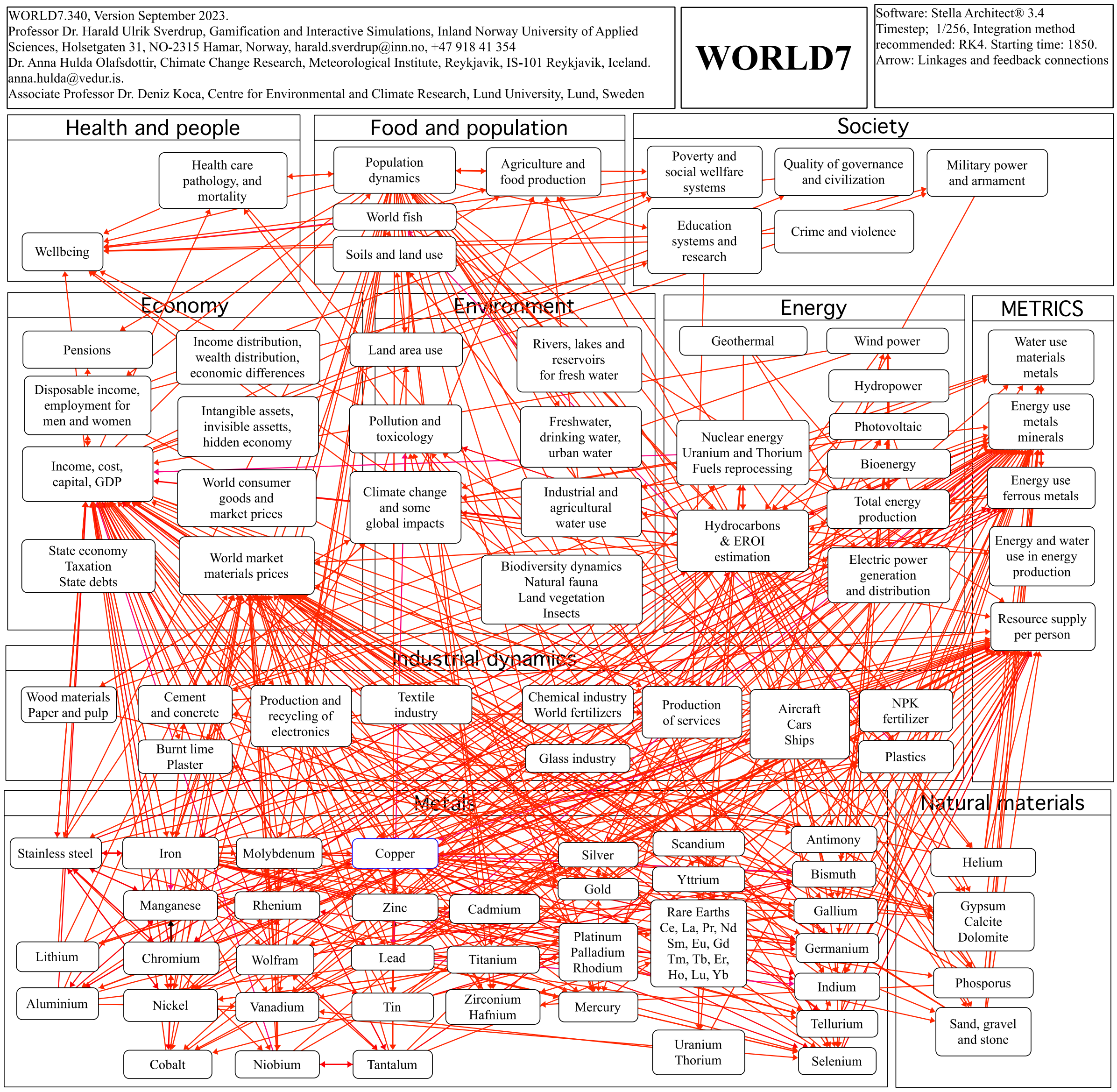


Fig. 7 An overview of the whole WORLD7 system, version 7.358 of 1 September 2023

demand for each of them. All show peak behaviour due to the intended international UN/ECE environmental policy to phase cadmium totally out of use in society.

Figure 9e shows the simulated degree of recycling to society and the flow to the permanent final deposit of cadmium. The captured fraction of supply exceeds the value one when the stocks-in-use declines and as cadmium is phased out. This is a sign of cadmium being long term removed from the system.

Figure 9f shows the simulated amount lost to the environment. First, the cadmium ban creates a collapse of the demand and the price and, later, an increase when there is a lack of production capacity.

The amount of cadmium lost to the environment from 1900 to 2200 is about 700,000 tons. During the same period, about 1 million tons will have been captured and sent to the final safe repository. Figure 9g shows the price simulation for cadmium. Figure 7h shows the cumulative amount of cadmium demand,

Table 4 Parameterization of the cadmium sub-model rate coefficients used in the WORLD7 model simulations

Parameter	Value set in the model
Society retention, plating	10 years
Society retention, alloys	30 years
Society retention, batteries	15 years
Society retention, PV	30 years
Society retention, colours	10 years
Recycling yield, %	80
Numerical time-step	1/365 year
Numerical integration method	4-step Runge–Kutta
Simulation time	1850–2200

modified demand, supply and extraction. Note how soft scarcity sets in 2020, when demand and modified demand separate. Modified demand and supply will separate in 2100, signalling hard scarcity.

4.2 Testing the Model

The model has been tested against the recorded mining data derived from the USGS (2022) databases. Figure 10a shows a comparison of simulated extraction as compared to the data. Figure 10b shows the cumulative extraction as compared to the cumulative simulated amount. The fit is excellent. There is no systematic error building up in the model with time, suggesting the model gets the mass balances right. Figure 10c shows the simulated price as compared to the observed data. Figure 9d shows the stocks-in-use in kg per capita and supply in kg per capita and year. It shows a typical peak behaviour caused by the phasing out of cadmium rather than because of significant scarcity. Take note that the cadmium module inside the WORLD7 model is not calibrated to any production data, but does this up from basic principles of trade, economics of supply and demand and mining dynamics. This can be seen throughout the results section and in the comparisons with data. The model does reproduce the observed mining rates satisfactorily when the model is driven by market demand and price dynamics. All metals, minerals and commodities are modelled simultaneously this way in WORLD7 without any time-series calibration.

5 Discussion

5.1 Environmental Concerns versus Technical Usefulness

The cadmium supply has peaked and is declining according to the international plan to phase it out of all uses. Cadmium is a technically useful metal, but its very significant toxicity is a problem that cannot be ignored. Cadmium is one of the metals that will be phased out in Europe in accordance with the LRTAP1996 Heavy Metals Protocol (UN/ECE-LRTAP, 1998). The use

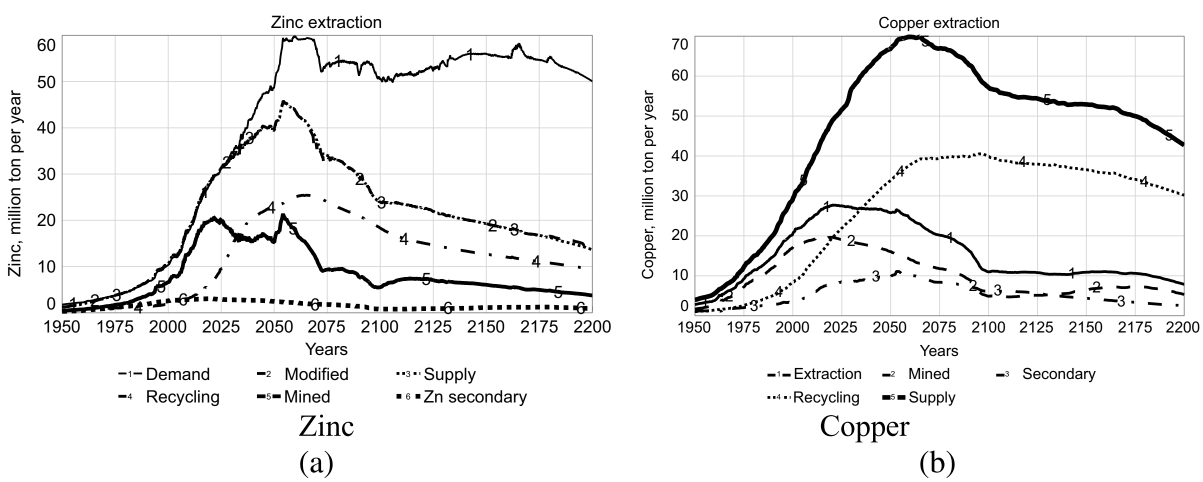
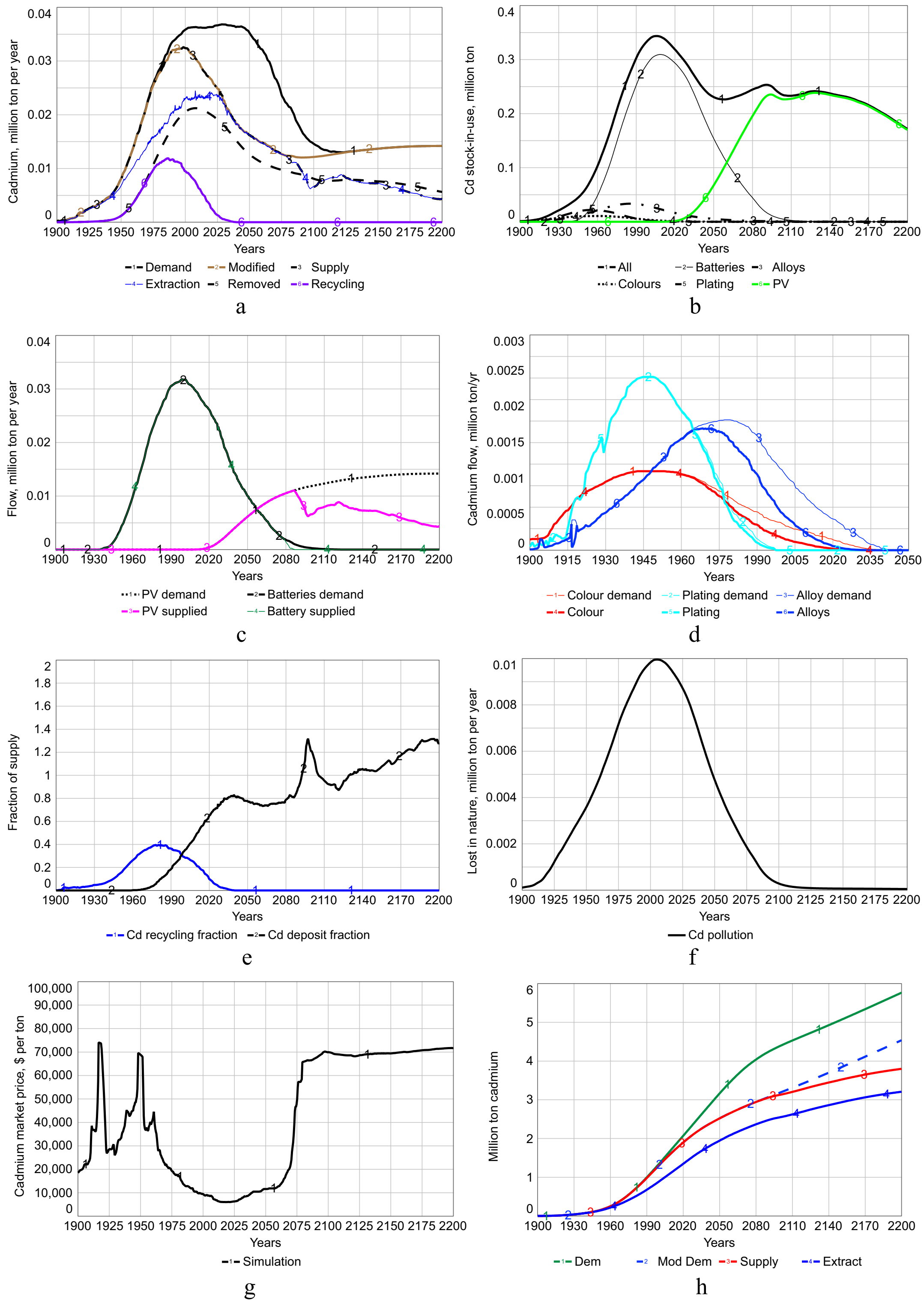


Fig. 8 The primary extraction rate of the source metals (**a**) zinc and (**b**) copper in the WORLD7 model (see Sverdrup et al., 2019, for a full description)


Cadmium, million ton per year
Years
Demand
Modified
Supply
Extraction
Removed
Recycling
a
Cd stock-in-use, million ton
Years
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PV demand
Batteries demand
PV supplied
Battery supplied
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Cadmium flow, million ton/yr
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Cd recycling fraction
Cd deposit fraction
e
Lost in nature, million ton per year
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Cd pollution
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Cadmium market price, $ per ton
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Million ton cadmium
Years
Dem
Mod Dem
Supply
Extract
h

◂**Fig. 9** Results from the WORLD7 model simulations. (**a**) The extraction, loss, supply, recycling and removed from circularity. (**b**) The demand to different sectors. (**c**) The flow to cadmium uses. (**d**) The cadmium stocks-in-use and amount of waste in scrap. (**e**) The price simulation for cadmium. (**f**) The fraction of supply as recycled and how much is captured and sent to final deposit. (**g**) The simulation of the cadmium price. (**h**) The cumulative amount of cadmium demand, modified demand, supply and extraction

of cadmium is restricted in Europe because of human health risks. Cadmium is very toxic, and a serious poisoning has virtually no cure. It is still used in electric accumulators, but these may eventually be phased out. If cadmium can be used for CdTe solar cells on a large scale, it appears uncertain; it will be dependent on whether a significant cadmium recovery after use can be done or not. Unless near recapture of the used cadmium in the new technical applications, it would probably not be permitted. For cadmium, the underproduction is caused by the environmental policy in Europe on cadmium due to its great toxicity (UN/ECE-LRTAP 1998, Genchi et al., 2020, Nriagu & Pacyna 1988). Cadmium supply per person per year is shown in Fig. 9d. In the long run, the success of the UN/ECE-LRTAP 1998 protocol will be determined by the degree of global enforcement as well as unintentional and intentional policy leakage. It must be counted on that lobbying will be brought on to make exceptions for cadmium use in alternative energy technologies such as photovoltaic panels of the CIGS type and some types of batteries. This will be argued on the great need for energy and pointing to the smaller hazard of using cadmium in photovoltaic panels as compared to the damage from large scale use of coal for power generation.

5.2 Environmental Impacts of Cadmium Use, Pollution and Human Exposure

Figure 9f shows the predicted loss rate to the environment per year from the technical sphere of the model simulations. In total, 970,000 tons of cadmium is lost to the environment that originated from mined cadmium. Much of the technically lost cadmium ends up in the environment. In addition to this comes a significant cadmium flow to the environment and humans from the use of agricultural fertilisers which have cadmium contamination in the phosphate deposits (Nriagu & Pacyna 1988, Pacyna & Pacyna 2001). This is an issue when sedimentary cadmium is used. The main global phosphate resources are of the sedimentary type, such as those from Morocco.

Figure 11 shows the flow chart for the interaction between society and the environment for cadmium. This system is also contained in the WORLD7 model where it interacts with public health, hospitalizations and mortality, and with the population model. These aspects do not come into this narrative in any detail and will be the subject of a later study. Cadmium reaches humans through several pathways, the two most important being through contaminated food and secondarily through environmental pollution. In earlier times, the use of cadmium in consumer products caused significant exposure.

Cadmium is a volatile element with low melting and boiling points and thus can also escape from technical environments easily. However, cadmium is not long lived the environment. Under anaerobic conditions, cadmium encounters sulphide ions and is very strongly bound as cadmium sulphide that will not readily redissolve. Recycling of cadmium from technical uses has challenges, but work is being done to improve recycling (Feddersen & Lee, 1954; Marwede & Reller, 2012, 2014; Reuter et al., 2013a, 2013b).

Figure 12 shows the dose–response diagram for mercury, cadmium and lead as derived many years ago from literature data by some of the authors (Bakker et al., 1998; Friberg et al., 2019; Pfitzer & Vouk, 1979; Sverdrup, 2001; Sverdrup & Ashmore, 2001). The authors did a more recent review of some literature (Balali-Mood et al., 2021, Bernhoft, 2012; Buchet et al., 1980; Chen et al., 2006; Chen et al., 2019; Choong et al., 2014; Li et al., 2019; Lin et al., 2018; Lv et al., 2017; Djordjevic et al., 2019; Järup et al., 1998; Nishijo et al., 2017; Perry & Erlanger, 1974; Proshad et al., 2020; Rani et al., 2014; Satarug, 2018; Satarug et al., 2000; Yang & Shu, 2015; Kjellström & Nordberg, 1978; Mezynska & Brzóska, 2018; VKM, 2015; Food Safety News, 2012; ANSES, 2019; Shar et al., 2012), as confirmed the picture shown in Fig. 12. The picture was radical in 2001, and in 2023, it appears as very appropriate and in line with the latest research on their topic. Cadmium is very toxic, and there is no valid lower limit. Take careful note that mercury and cadmium show the same dose–response system behaviour, despite the fact that the physiological mechanisms for effect are different. This stands in contrast to lead, where the medical effect disappears below 300 µg per day (Fig. 12). This difference arises

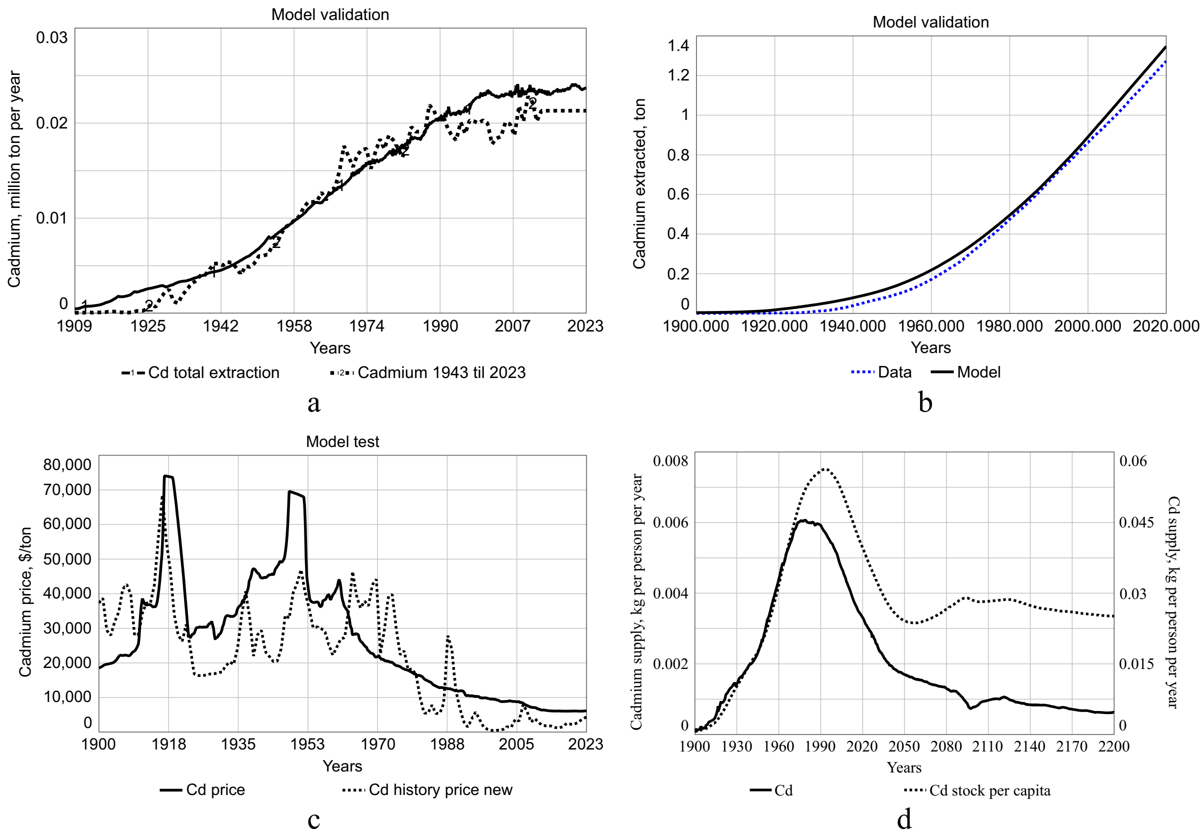

Fig. 10 Results from the WORLD7 model simulations. (**a**) A test of the model simulation against data for the cadmium extraction (**b**) and the cumulative cadmium extraction. (**c**) The cadmium price as simulated with the model versus data. (**d**) Supply per person and year in kg per person and year and stocks-in-use in kg per capita for Cd. The cadmium model captures the cadmium history with great accuracy

from the fact that the body can get rid of lead in small amounts through some mechanisms that move calcium in the body. For cadmium and mercury, there is no such mechanism. The diagram strongly suggests that there is no safe exposure level and that both mercury and cadmium are damaging from the first molecule of exposure.

Due to the volatility of cadmium and mercury and their methylated compounds, cadmium and mercury also move freely across any cell barrier, including the blood–brain barrier. The half-life time for cadmium in the body is 37 years, implying that there is no way for a normal grown-up person to recover from significant exposure (Kjellström & Nordberg, 1978, Chunhabundit 2016). Thus, long-term exposure and acute exposure of any kind must be avoided. Cadmium is as poisonous to animals as to humans, and the effects on the natural environment are very serious. The response function shown in Fig. 12 shows why it is urgent and necessary to have a total ban on all use of both cadmium and mercury (Balali-Mood et al., 2021; Sverdrup & Olafsdottir, 2020b) and why any exceptions to that rule must be so few that any cadmium leakage to nature is irrelevant. This dictates that the photovoltaic technologies listed in Table 3, as using cadmium, cannot be allowed until a recovery after use of at least 90% elimination of any leakage to nature can be guaranteed (EFSA, 2009). At present, the industry is very far from any such goal.

It would be technically possible to produce at least 250,000 tons of cadmium per year. In reality, the 2023 production is about 24,000 tons of cadmium per year in 2022. This much cadmium never reaches humans as the environment is in between, filtering out more than 99% of the cadmium pollution as an environmental service. Without this

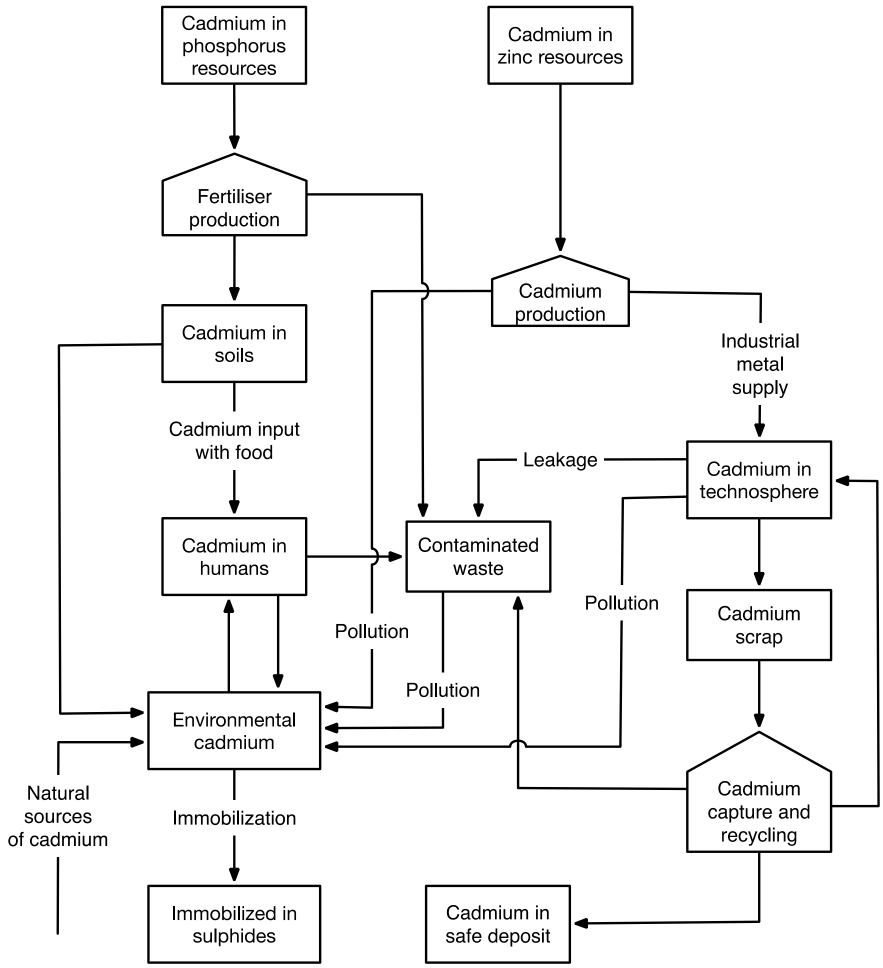

Fig. 11 The flow chart for the interaction between society and the environment for cadmium. The natural sources are few and small, and almost all cadmium exposure has some anthropogenic origin. Besides food, tobacco can also provide cadmium exposure

environmental service, humanity would have been in deep trouble. The background cadmium exposure is at about 3 µg per day per person and is declining.

There is also a consequence for climate change mitigation and adaptation. Several metals set limits for how much photovoltaic capacity can be installed in the future as a compensating effort when fossil fuels are phased out from 2025 to 2050. Preliminary calculations (Sverdrup & Ragnarsdottir, 2014; Sverdrup & Olafsdottir, 2020b; Sverdrup et al., 2024) suggest that the amounts extractable for indium, gallium, germanium, cadmium, and silver are sufficient for about 20–25% of the projected demand for solar photovoltaic power. This emphasises renewable energy for solar photovoltaics that will not be able to replace the energy not made when fossil fuels are phased out. For climate mitigation and adaptation measures to be successful, a strategy with different new technologies and significant reductions in total energy use will be required. This is much talked about in preambles and prefaces to different strategy documents, but is absent from most action plans.

5.3 Sustainability of Supply

In the model, the demand is made on the market, and when the market amount goes low, then the prices go higher. Figure 10d shows the supply per person and year in kg per person and year and stocks-in-use in kg per capita for Cd. The supply per person and year must cover up for wear and losses, use for maintenance, and any extra over that can allow growth. If less is supplied than the losses, then the stock will decline. Higher prices push the mining rate by increasing profits, causing the price to increase, which in turn makes the demand decrease. The model becomes self-regulating. The market

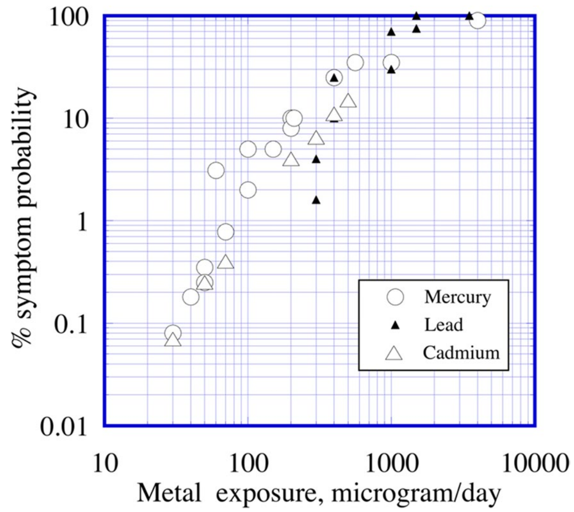

Fig. 12 Dose–response diagram for mercury, cadmium and lead as derived many years ago from literature data by some of the authors (Bakker et al., 1998; Sverdrup & Ashmore, 2001; Sverdrup & Olafsdottir, 2020b; Genchi et al., 2020) for use in the UN/ECE-LRTAP convention and the 1998 Århus Heavy Metal Protocol. Median consumption in the USA was 0.16 µg per kg body weight per day

dynamics are fully expressed in the present cadmium model and that gives a significantly smoother production curve and better dynamics. This is the case for all minerals, metals and commodities represented in the WORLD7 model. In the discussion of sustainability, we should note that recycling can delay symptoms of scarcity for a significant time, even after the primary production from mines has stopped. Supply per person and year reflects the amount available to compensate for continuous losses and any surplus available for growth in the stock-in-use. Stock-in-use per person is an indicator of the utility gained from the resource, and a decline in stock-in-use suggests a decline in service provision from that resource. The production of the dependent metals is limited to some extent by the fact that only a fraction of the metal refineries is technically equipped for efficient recovery of these metals.

6 Conclusions

The case of cadmium represents a classical conflict of goals. Present and future energy needs stand in opposition to the protection of the natural environment and human health. All types of available photovoltaic technologies will be required for reaching sufficient amounts of renewable energy in order to replace fossil fuels before 2050 (Sverdrup et al., 2022). At the same time, it is of great importance to phase out cadmium, potentially taking away 25% of the future photovoltaic capacity that will be available (Sverdrup et al., 2024). From earlier studies (Sverdrup & Ragnarsdottir, 2014, Sverdrup et al., 2022), we do know that indium, gallium and silver will limit the photovoltaic technologies using indium, gallium and silver by 75% as compared to the projected activities. This is a very serious warning that there is something fundamentally wrong with the projections of future capacity for solar electric power on a large scale. All of this urges towards doing research to substitute cadmium with something less toxic in solar photovoltaic panels and battery technologies.

There is no shortage of cadmium to extract, and no shortage from lack of cadmium available in the future zinc flow is to be expected. Thus, from a technical perspective, all cadmium demanded can be supplied. It would be possible to produce at least 250,000 tons/year; in reality, the 2023 production is about 24,000 tons/year and declining. This is so low in 2022 because there is a United Nations agreed global policy to phase out cadmium from all use. Technical demand for cadmium will soon not be met, and there will be an actual shortage of cadmium for any use, including photovoltaic technologies and semiconductors. This is very good news for the environment and human health, but bad news for those that want the CdTe and CIGS types of photovoltaic panels to mitigate future energy shortages. There are strong arguments against allowing the use of cadmium in applications where recycling is problematic. For photovoltaic panels using cadmium as an ingredient, the recycling degree is very poor, far from what must be demanded for cadmium.

The environmental policy of the UN/ECE-LRTAP Convention has been successful, and it seems like cadmium will probably be phased out of all use, including photovoltaics. Thus, pursuing research towards any technology that uses cadmium does not seem to be a good business strategy. A departure from the heavy metals policy should only be permitted if a better than 95% recapture efficiency can be secured for the cadmium used.

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Author Contribution Dr. H. Sverdrup developed the cadmium module for the WORLD7 model, as well as the cadmium toxicity module in the public health assessment module. The human dose–response data and the response function were developed by Sverdrup and colleagues about 25 years ago in projects for the LRTAP convention (Sverdrup, 2001; Sverdrup & Ashmore, 2001). Sverdrup wrote up the first manuscript draft and did the simulation runs. Ole van Allen worked on the further general development of the WORLD7 model into European resource-integrated assessment platforms. Dr. Hördur Valdimar Haraldsson participated in the environmental assessment and developed the relevance to the European Environmental Policy, cross-cutting to public health and heavy metal regulations.

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Data Availability There are no databases associated with this study that can be shared. All data used were taken from open public sources or scientifically published sources. The model is available in STELLA Architect format upon request from the corresponding author.

Declarations

Ethics Approval This work is original research done by the authors. All text herein comes from the hands of the authors and nowhere else. No artificial intelligence language models were used in creating this work.

Conflict of Interest We declare that we have no conflict of interest within the field of cadmium nor any vested interests in the cadmium sector. H. Sverdrup has worked in the past with assessments concerning setting limits for heavy metals for UN/ECE-LRTAP 1990–2002.

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