Static and dynamic flows of BFRs(PBDEs) in TVs from E-waste and environmental Implications

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I Research Background and Objectives

1. Background
2. Objectives

1.1 Research Background: e-waste and BFRs

■ E-waste is one of the fastest-growing environmental problems worldwide

- High volume and widespread use of electrical and electronics in developing and developed countries
- Shorter life span of appliances and electronics
- As a result, a tremendous amount of e-waste is generated everyday

■ Toxic chemicals (heavy metals, PBDEs) may causes toxic hazards in human health and in the environment

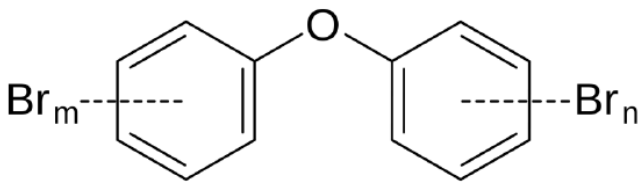
- E-waste often contains recyclable materials as well as toxic chemicals (flame retardants, lead, mercury, arsenic, and many other chemicals)

■ Proper management practices of e-waste are needed towards a circular economy

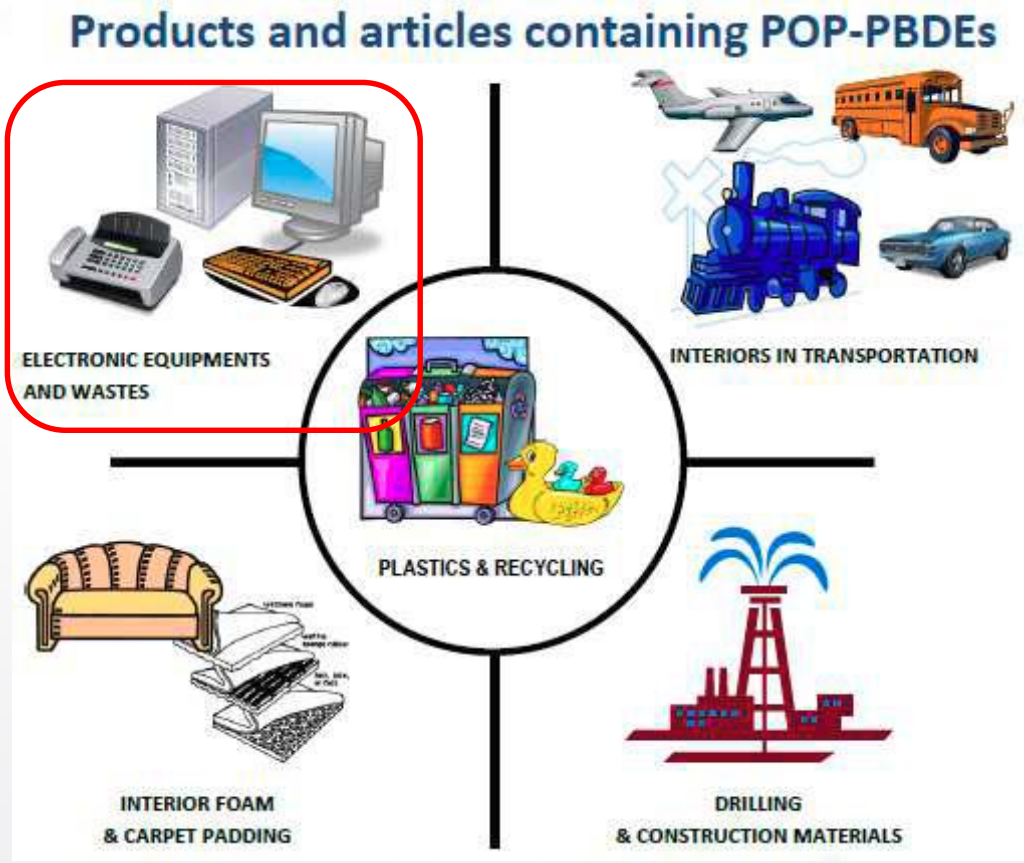
- Need to recover valuables from e-waste for secondary materials towards a circular economy
- Require special handling and guideline to avoid potential exposure and minimize environmental contamination
- There are still lack of management guidelines and regulations on BFRs in e-waste streams in many countries
  - Appropriate management plan can help protect human health and the environment

1.2 Research Background: Major use of PBDEs

- Major historical use of PBDEs include electronics, transportation, furniture, constructions
- Tetra-BDE, penta-BDE, hexa-BDE, hepta-BDE(2009), deca-BDE(2017) are listed in POPs by Stockholm Convention



Chemical structure of PBDE



(Source: UNEP, 2016)

1.3 Research Background: Estimated production of PBDEs

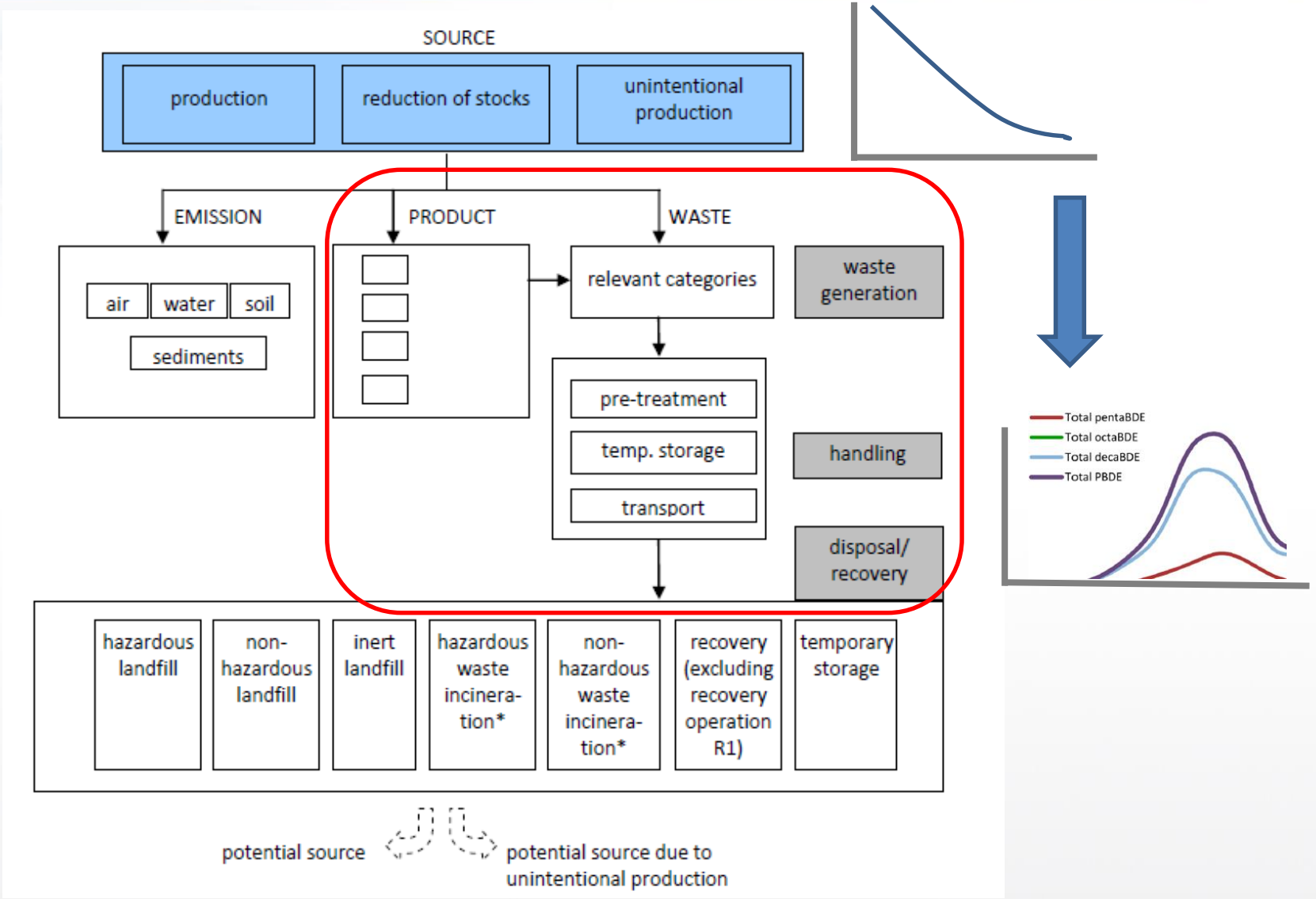
- Production of c-Penta-BDE and c-Octa-BDE have been stopped since 2004, while the production of c-Deca-BDE has been continued (approximately 1.1~1.25million ton)
- In EU, the use of c-Deca-BDE was prohibited after March 2, 2019 (2017/2/10 EU Regulation)
- In the US, a similar trend of restricted use of PBDEs is observed by voluntary agreement for phase-out

<Table> Estimated total production of PBDEs in the world

Commercial mixture	Tonnes
c-PentaBDE	91,000 to 105,000
c-OctaBDE	102,700 to 118,500
c-DecaBDE	1,100,000 to 1,250,000

(Source: UNEP, 2016)

1.4 Research Background: Mass flow of PBDEs



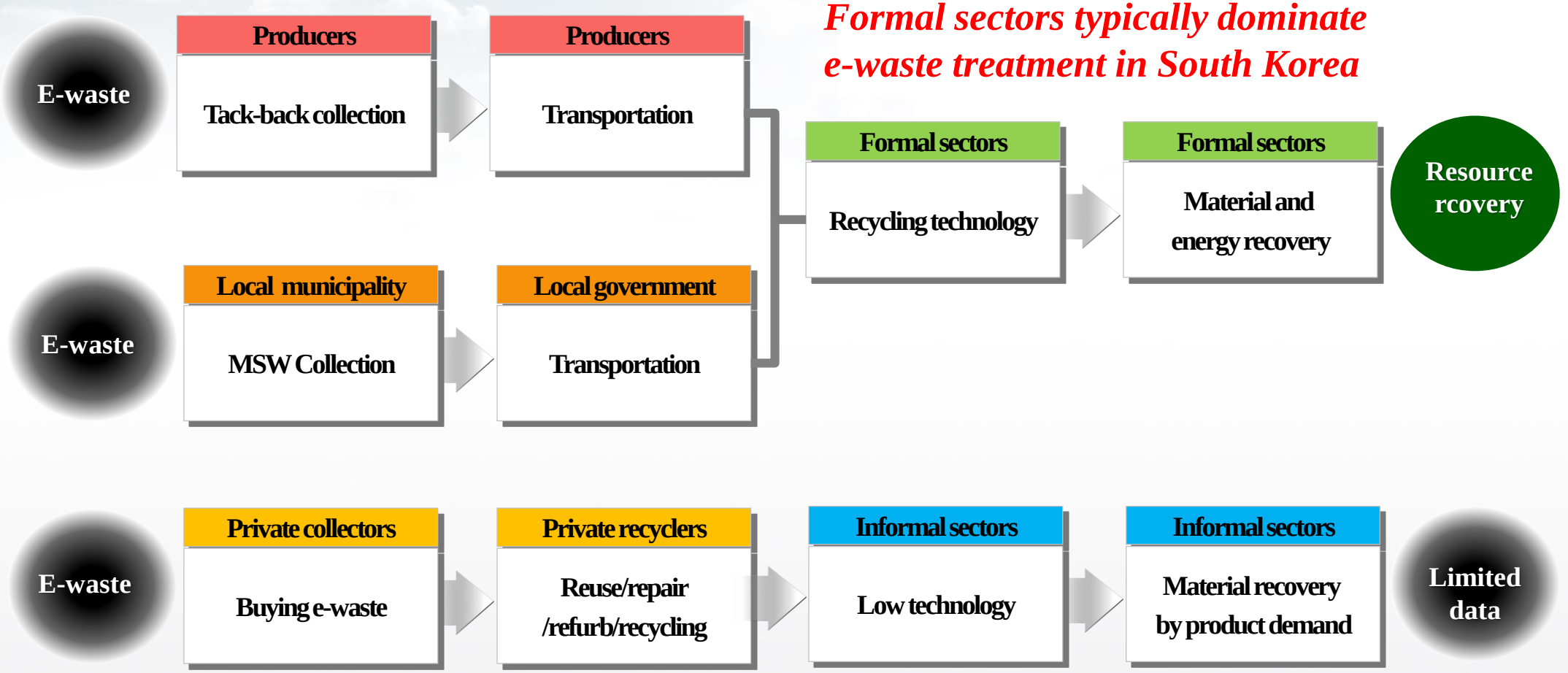
<Fig> Substance flow of PBDEs

(Source: European Commission, 2011)

1.5 Research Background: E-waste pathways in South Korea

■ **E-waste Management Pathways**

(Three pathways for collection and recycling of e-waste)

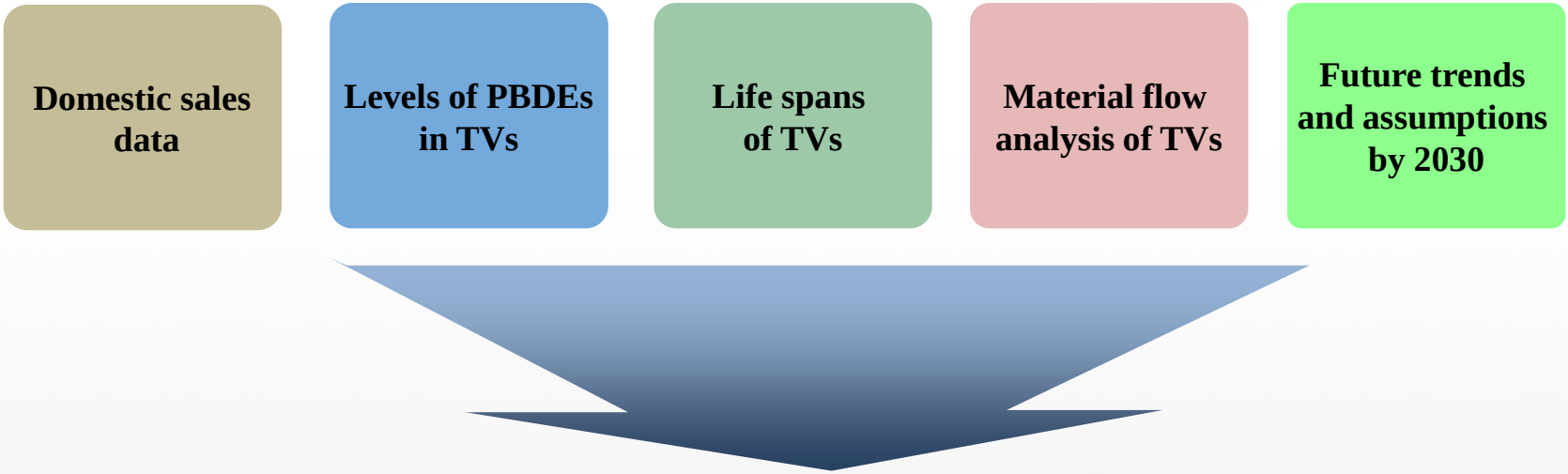


Formal sectors typically dominate e-waste treatment in South Korea

1.6 Research Objectives:

Research QUESTIONS?

1. What are levels of PBDEs present in TVs from e-waste streams?
2. What are the average concentrations of PBDEs in TVs waste over time?
3. How much PBDEs from TVs in South Korea are generated by 2030?
4. What are environmental implications based on substance material flow of PBDEs in e-waste streams?

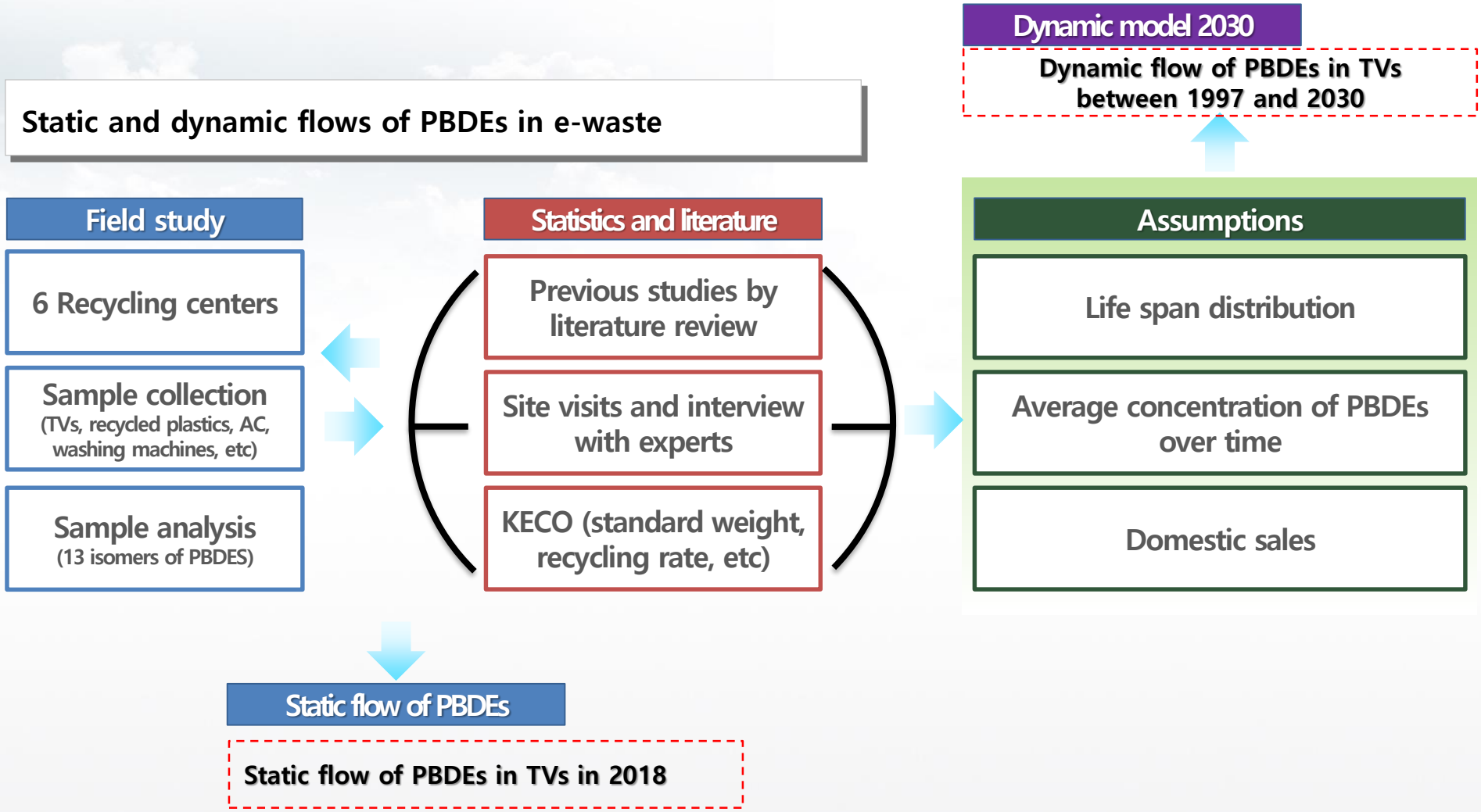


“How much BFRs(PBDEs) would be generated from TVs waste by 2030?“

II Methodology

1. Approach for static and dynamic flows of PBDEs in TVs
2. Sample collection and analysis
3. Assumptions for dynamic flow of PBDEs by 2030

2.1 Method: Approach for static and dynamic flows of PBDEs in e-waste (TVs)



2.2 Method: Sample collection

- A total of 97 samples from six recycling centers were collected
- A total of 30 samples of TVs were analyzed for PBDEs and HBCD

Table 1. Sample collection and information for products and wastes containing BFRs in

Category	Targets	Sampling site	Products
Electrical and electronic equipment (EEE)	TV	Recycling center (A, B, C, D, E, F) research institute	CRT TV/LCD TV

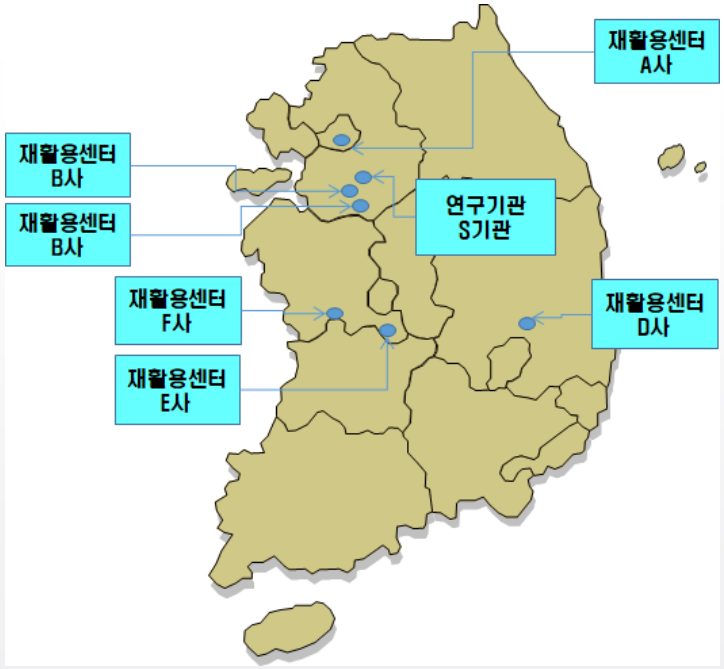
2.2 Method: Sample collection

<Sampling collection > (total: **97 samples**)

Site	category	product	Year
Recycling center: 6	TV (**30**)	CRT TV	1990~2013
		LCD TV	2007~2014
		Monitor	
	Other e-waste items (31)	printer	
		Rice cookers	1998~2013
		iron	
		Hair dryer	
		Multi-tap	
		AC	2006~2015
		Electrical Fan	2002~2012
	Shredded plastics (36)	Recycled plastics	





2.2 Method: recycling process and sample collection

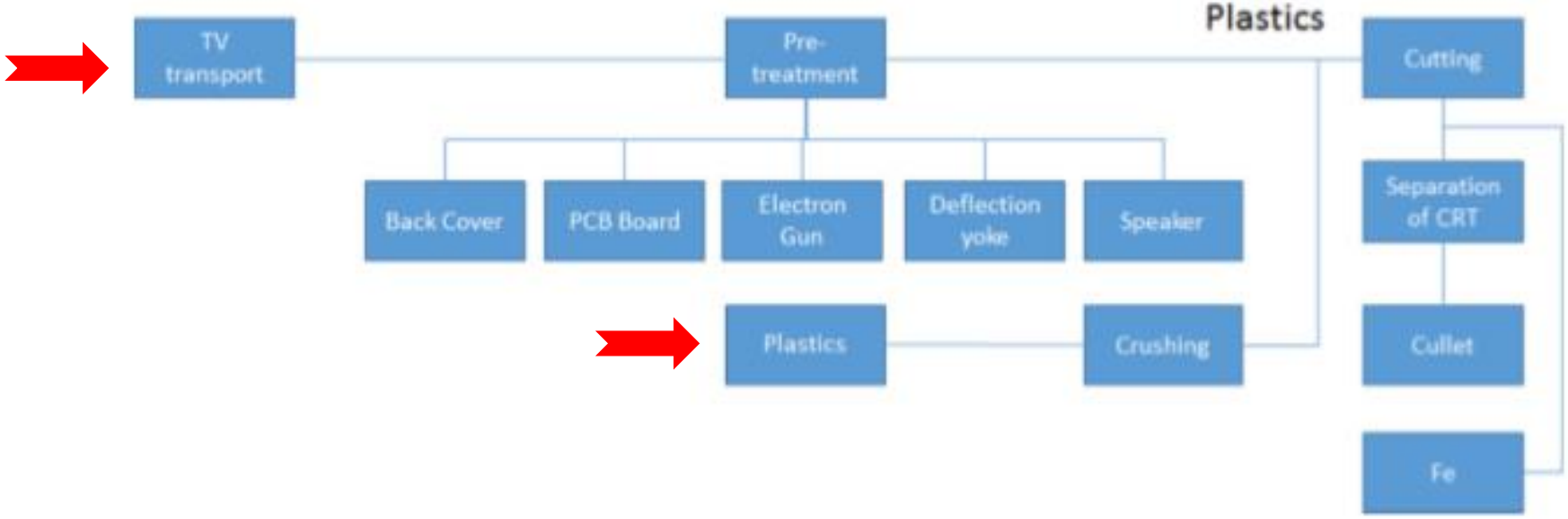


Fig. 1. Recycling process of recycling center C.

2.2 Method: recycling process and sample collection

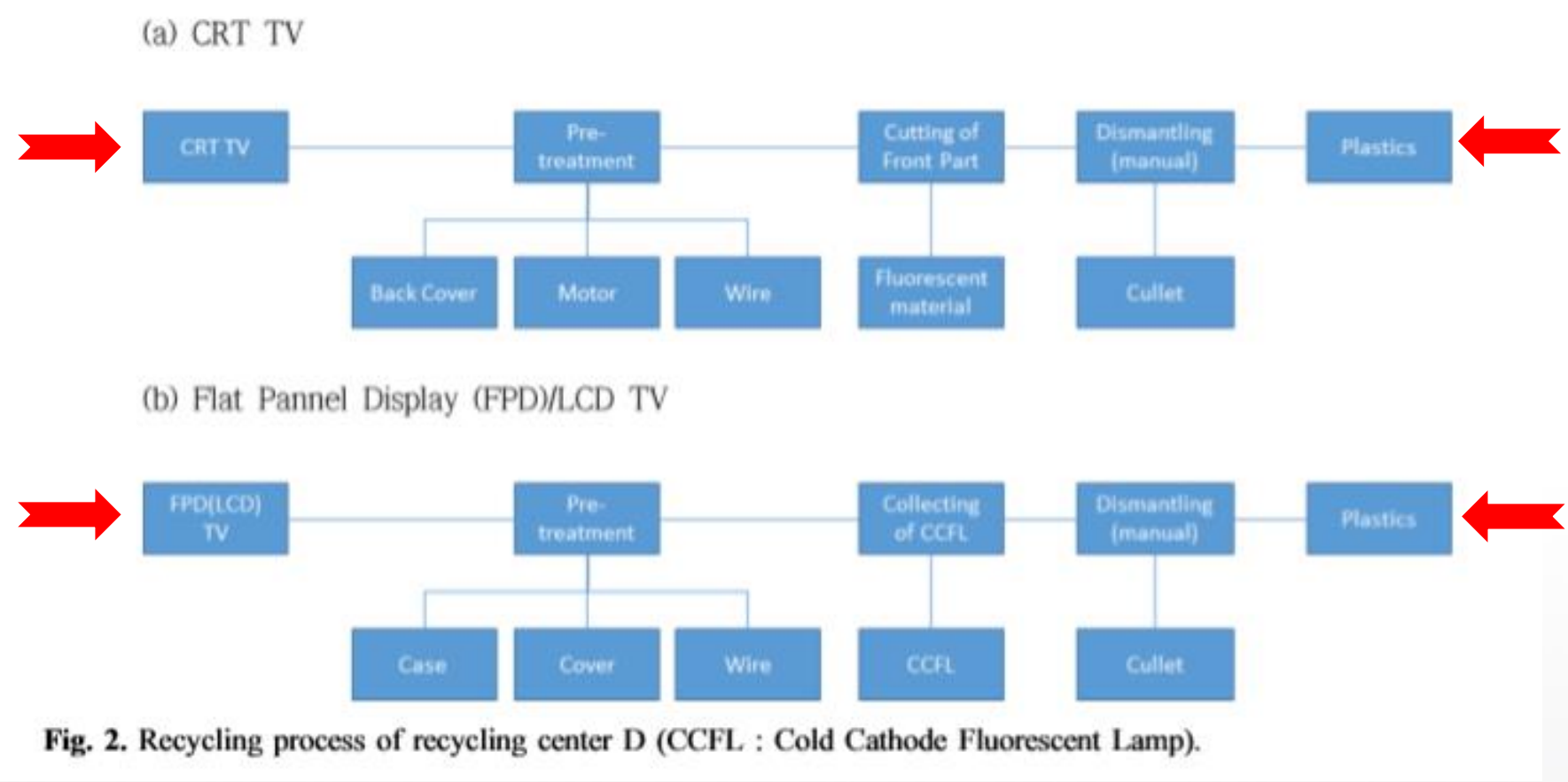
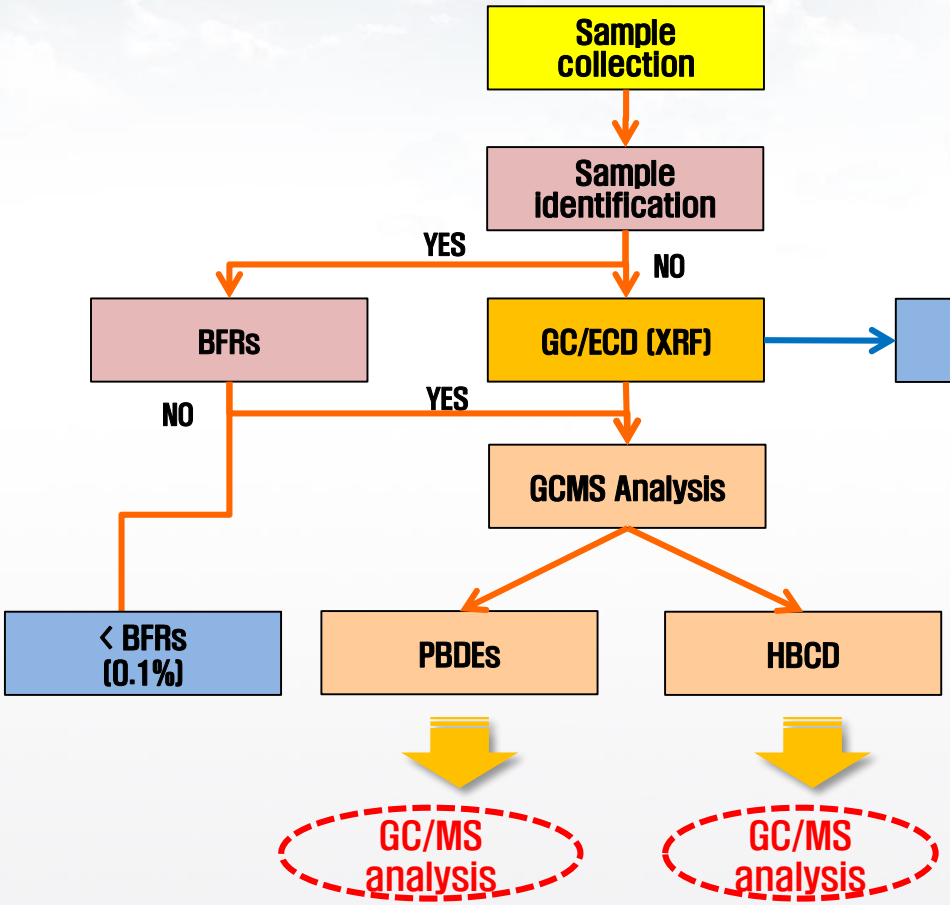
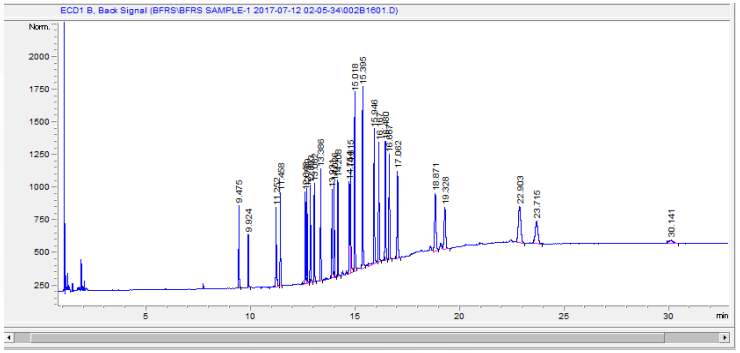


Fig. 2. Recycling process of recycling center D (CCFL : Cold Cathode Fluorescent Lamp).

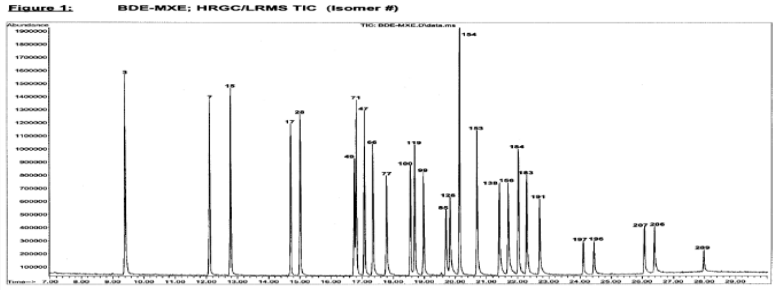
2.2 Method: Sample analysis with XRF & GC-MS

Sample analysis for BFRs

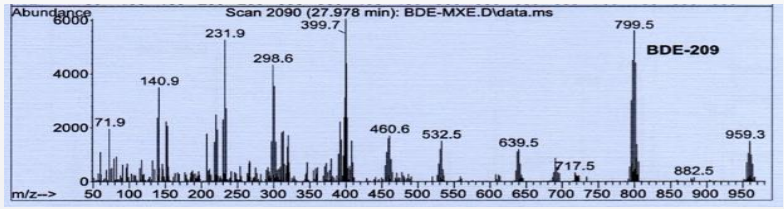




◆ PBDEs(GC/ECD) Chromatogram



< PBDEs STD (GC/MS) chromatogram>



< PBDEs Mass Spectra (BDE-209>

2.3 Method: additional data for material flow analysis

- Previous study was reviewed for material flow analysis of PBDEs in TVs
- Available statistics (recycling rate, domestic sales, disposal methods, etc) and field surveys were acquired for the MFA

Table 2. Data acquisition methods and Route for material flow analysis of TVs and PBDEs

Section	Life cycle	Statistics	Literature survey	Field survey
TV	Manufacture	○		○
	Use		○	○
	Disposal[a)]		○	○

a) Disposal : Inclucing collection, treatment, Recycling and final treatment

2.3 Method: Estimated concentrations of PBDEs in TVs (mg/kg)

Table 3. PBDEs content trend by TV production year

	Year	a[27]	b[26]	This study	Average	Trend
1	`83		12.20%		12.20%	11.90%
2	`84					11.38%
3	`85					10.86%
4	`86					10.34%
5	`87					9.82%
6	`88		17.20%		17.20%	9.30%
7	`89		12.00%		12.00%	8.78%
8	`90	8.90%	11.80%	<0.01%	6.90%	8.26%
9	`91	9.08%	14.30%	<0.01%	7.79%	7.74%
10	`92	10.00%		0.54%	5.27%	7.22%
11	`93					6.70%
12	`94	8.80%			8.80%	6.18%
13	`95		14.40%	<0.01%	7.20%	5.66%
14	`96			0.86%	0.86%	5.14%
15	`97		12.50%		12.50%	4.62%
16	`98					4.10%
17	`99			<0.01%	<0.00%	3.58%
18	`00		0.04%	1.85%	0.95%	3.06%
19	`01		0.57%		0.57%	2.54%
20	`02			0.25%	0.25%	2.02%
21	`03			<0.01%	<0.00%	0.98%
22	`04					0.46%
23	`05			0.85%	0.85%	<0.01%
24	`06			0.97%	0.97%	<0.01%
25	`07			<0.01%	<0.00%	<0.01%

2.3 Method: Life span distribution of CRT TVs

- Life spans of CRT TVs (yr=12.7) are used for the dynamic flow of PBDEs, as below

Estimated life spans of CRT TV

YEAR	before correction (%)	After correction (%)	Probability	lifetime*Prob
1	0.00	0.00	0.0000	0.00
2	0.00	0.00	0.0000	0.00
3	0.00	0.00	0.0000	0.00
4	0.38	2.77	0.0277	0.11
5	0.00	0.00	0.0000	0.00
6	1.14	2.47	0.0247	0.15
7	3.80	6.70	0.0670	0.47
8	4.56	5.43	0.0543	0.43
9	6.46	7.05	0.0705	0.63
10	8.75	8.85	0.0885	0.89
11	7.60	6.43	0.0643	0.71
12	13.69	9.75	0.0975	1.17
13	12.93	10.97	0.1097	1.43
14	6.84	6.69	0.0669	0.94
15	5.70	6.71	0.0671	1.01
16	5.32	6.59	0.0659	1.05
17	4.94	4.39	0.0439	0.75
18	5.70	4.88	0.0488	0.88
19	2.28	1.73	0.0173	0.33
20	4.94	4.27	0.0427	0.85
21	2.66	2.23	0.0223	0.47
22	1.52	1.32	0.0132	0.29
23	0.00	0.00	0.0000	0.00
24	0.38	0.37	0.0037	0.09
25	0.38	0.39	0.0039	0.10
	100.00	99.99	1.0000	12.74

III Results and Discussion

1. Concentrations of PBDEs in e-waste (TVS)
2. Static and dynamic flows of PBDEs in e-waste
3. Environmental implications

3.1 Results and discussion: PBDEs in e-waste (TVs and recycled plastics)

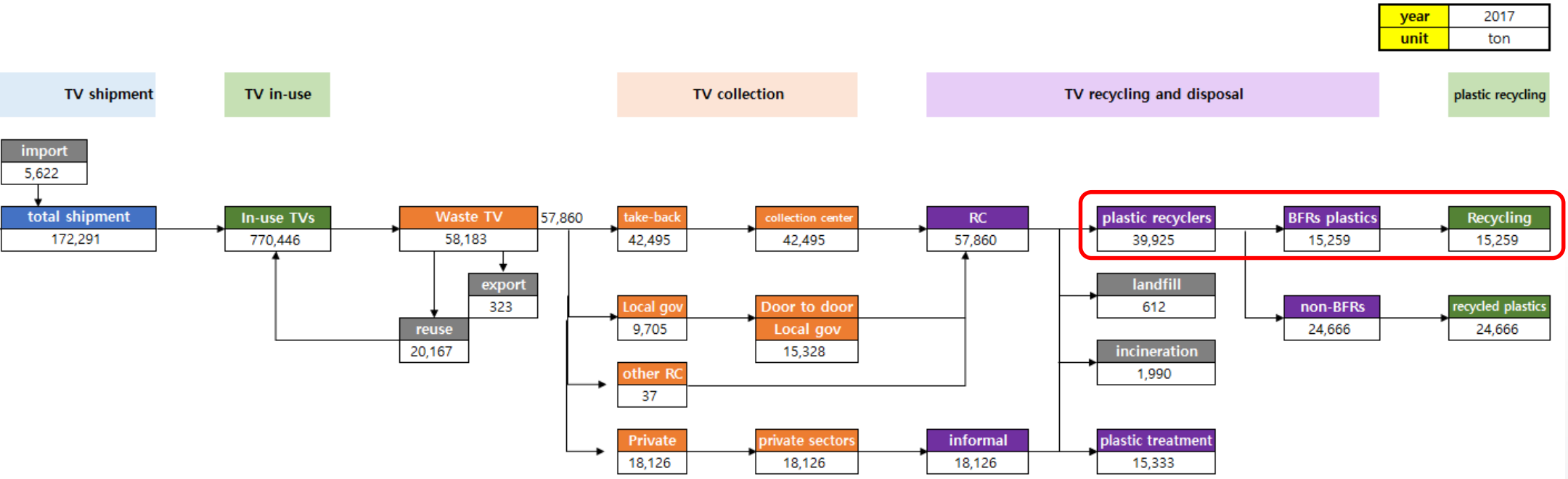
- The concentration range of TVs was from 135 to 18,500 mg/kg PBDE with an average of 7,739 mg/kg)
- PBDEs were detected with the concentration of 2,623 mg/kg in recycled plastics (19% detection rate)

Summary of PBDEs concentrations in e-waste

E-waste	category	Sampling sites	Products	This study (2017)									Previous study (2012)	
				No of samples	Detected samples		PBDEs (mg/kg)			HBCD (mg/kg)			PBDEs (mg/kg)	HBCD (mg/kg)
					PBDEs	HBCD	range	Ave.	STD	range	Ave.	STD		
E-waste	TV	Recycling centers	TV(CRT, LCD)	30	16(63%)	0(0)	135~18,467	7,739	4,283	N.D	N.D	N.D	19~ 145,027	N.D
	Small-size e-waste	Recycling facilities	Hair dryer/ printers/ iron/rice cookers	31	5(16%)	0(0)	102~1,354	435	368	N.D	N.D	N.D	N.D	N.D
	Recycled products	Recycling centers	Recycled plastics (PP/ABS/PS)	36	6(19%)	4(11)	134~5,626	2,623	2,056	18-13,405	3,383	5,045	199~ 25,066	1,929~4,060
total				97	41(18%)	14(6)	-							

3.2 Results and discussion: Static flow of TVs in Korea (2017)

- In 2017, approx. 40,000 ton of plastics from CRT/LCD TVs was recycled (15,259 ton with BFRs, 24,666 ton with non-BFRs)
- Most recycled plastics with BFRs flow into plastic extrusion recycling industry



3.2 Results and discussion: Static flow of PBDEs from TVs in Korea (2017)

- In 2017, 65 ton of PBDEs out of total 73 ton with BFRs in plastics from TVs was recycled
- No specific management guideline for plastic recycling industry with high concentration of PBDES is developed

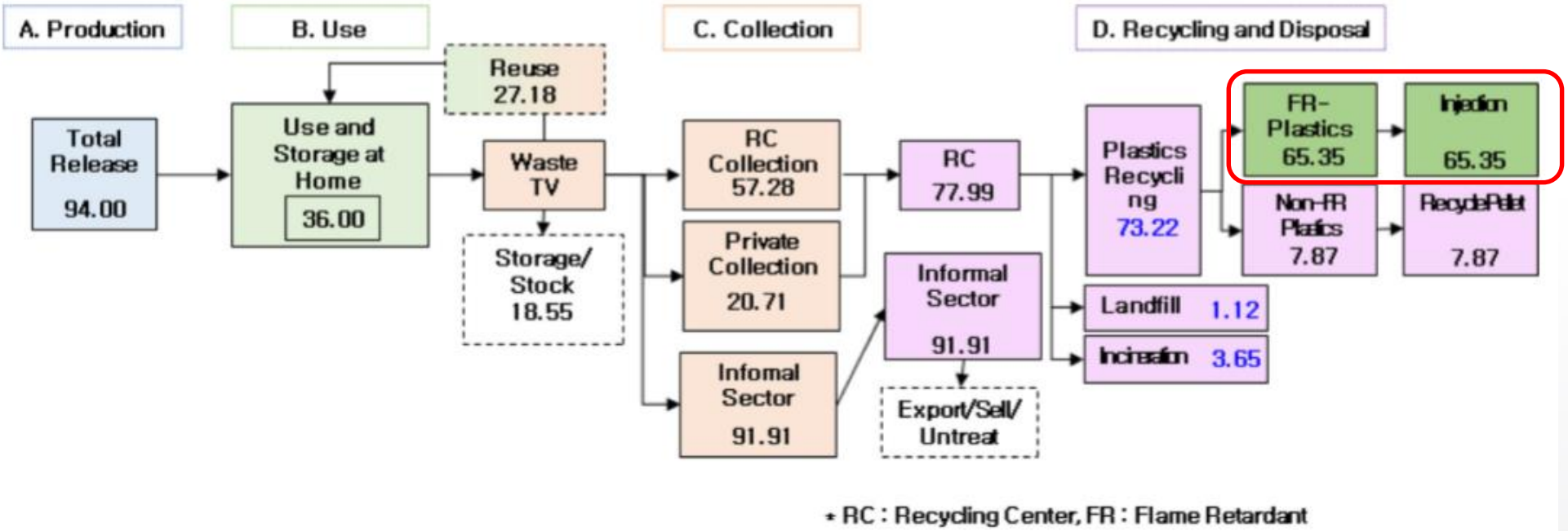
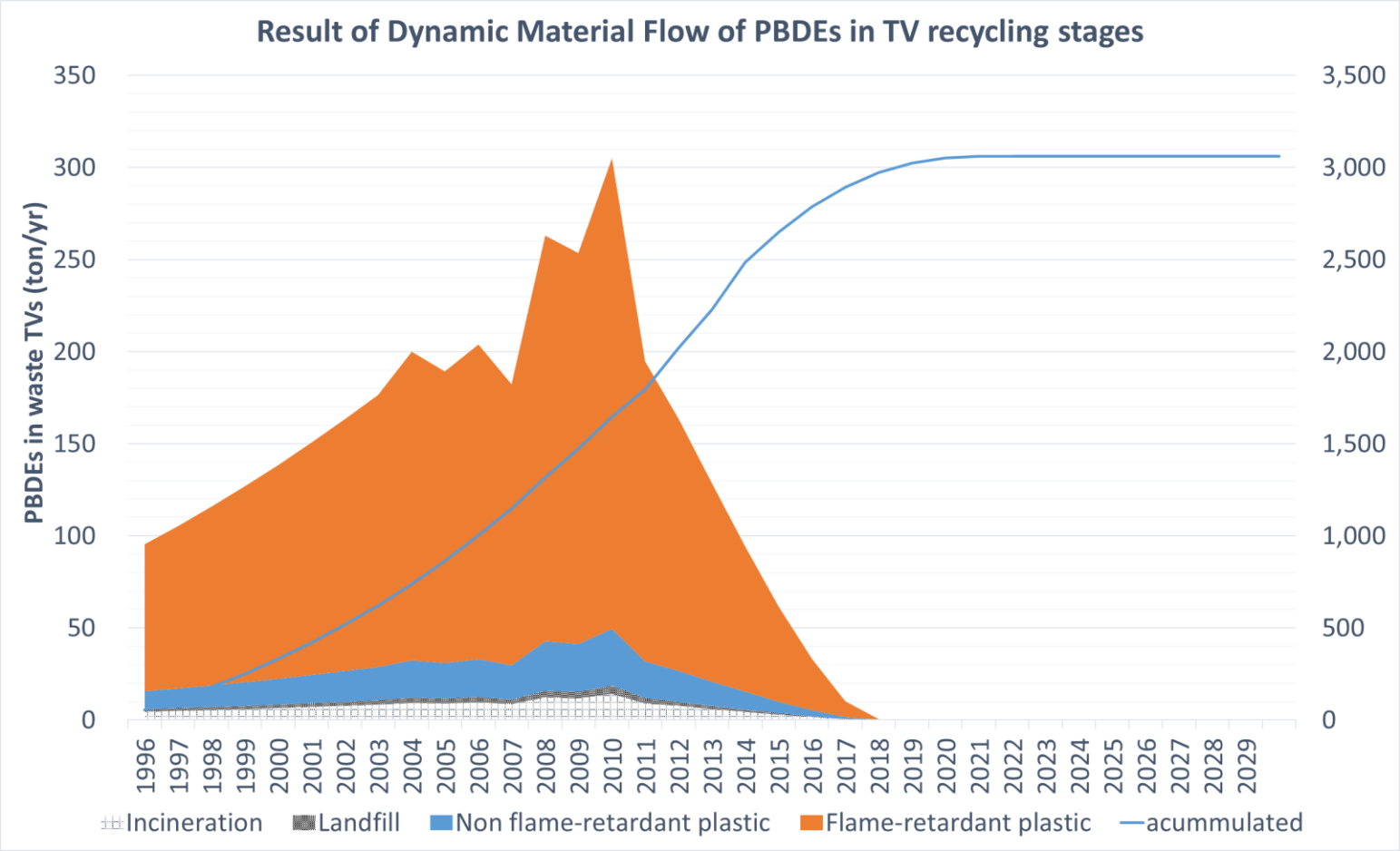


Fig. 4. Static MFA result of PBDEs in TV in 2017 (Unit : ton).

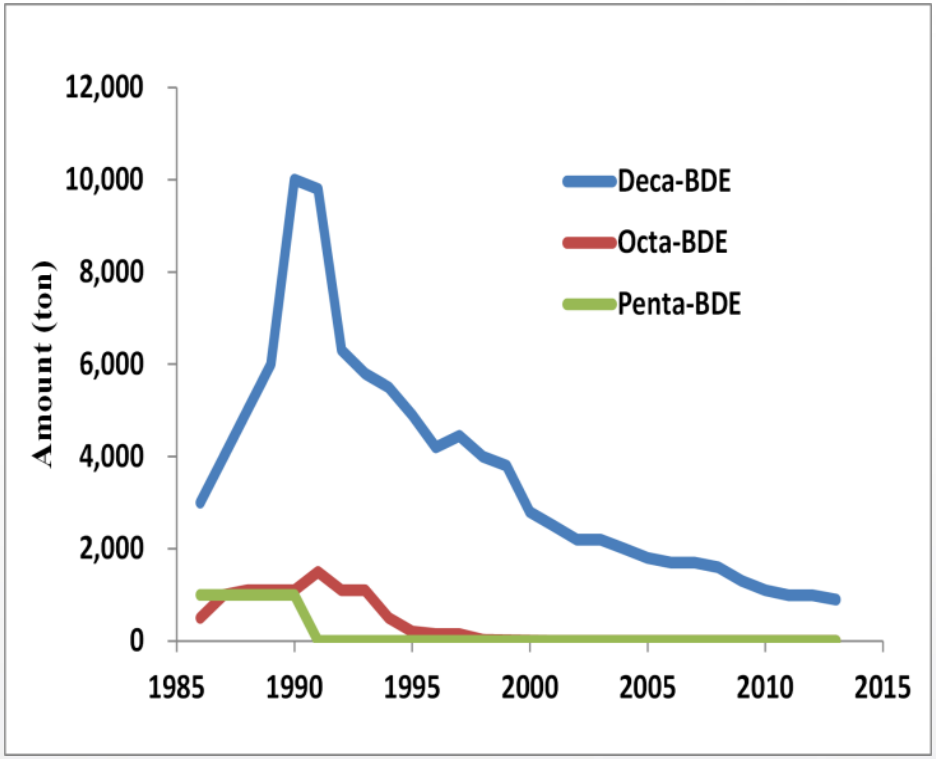
3.2 Results and discussion: Dynamic flow of PBDEs from TVs between 1997 and 2030

- The levels of PBDEs from CRTs TV dramatically decrease over time since 2011
- The total amount in recycled plastics with BFRs after TV waste recycling was estimated to be 3,000 ton. No detailed quantitative flow of such recycled plastics has been reported so far



3.2 Results and discussion: Use of PBDEs in Japan

- Use of penta-BDE, octa-BDE were banned in 1990 and 1999 in Japan.
- Use of deca-BDE is decreasing due to strengthened regulations in the world (recently, less than 1,000 ton per year.
- The historical use of PBDEs may be concerned over the time



<Fig> PBDEs Use in Japan (source: Dien et al., 2017)

3.2 Results and discussion: Prediction demands and in-stock of PBDEs in Japan

- In Japan, domestic demands of deca-BDE will continually decrease over time.
- The amount of in-stock of deca-BDE decreased from 28,000 ton in 2014 to less than 5,000 ton in 2040.

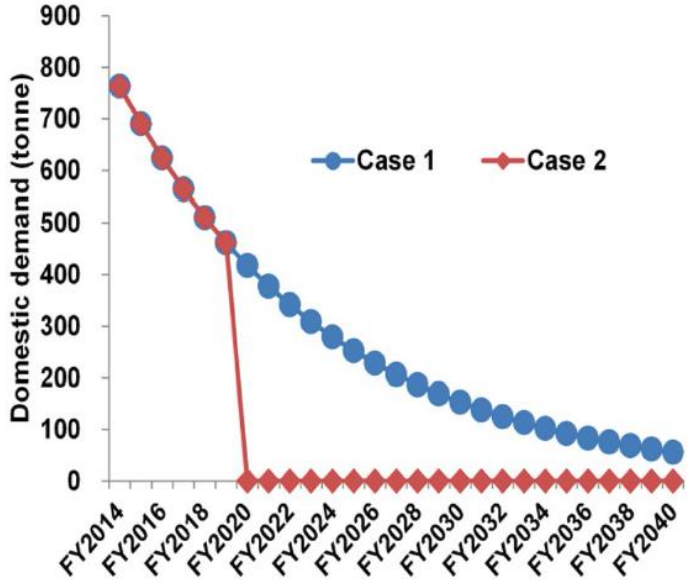


Fig. 5 Forecasted domestic demand for deca-BDE in Japan from 2014 to 2040, with case 1 where deca-BDE declines at the same rate as the current rate of decline, and case 2 where deca-BDE is discontinued after 2020

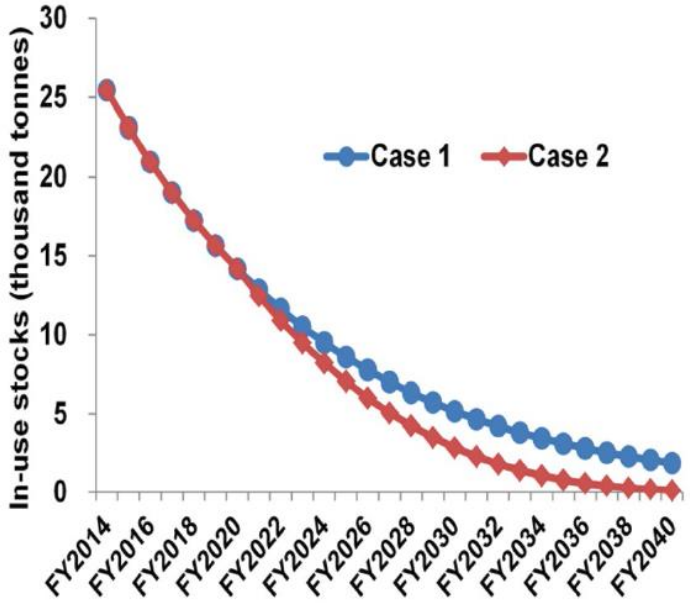
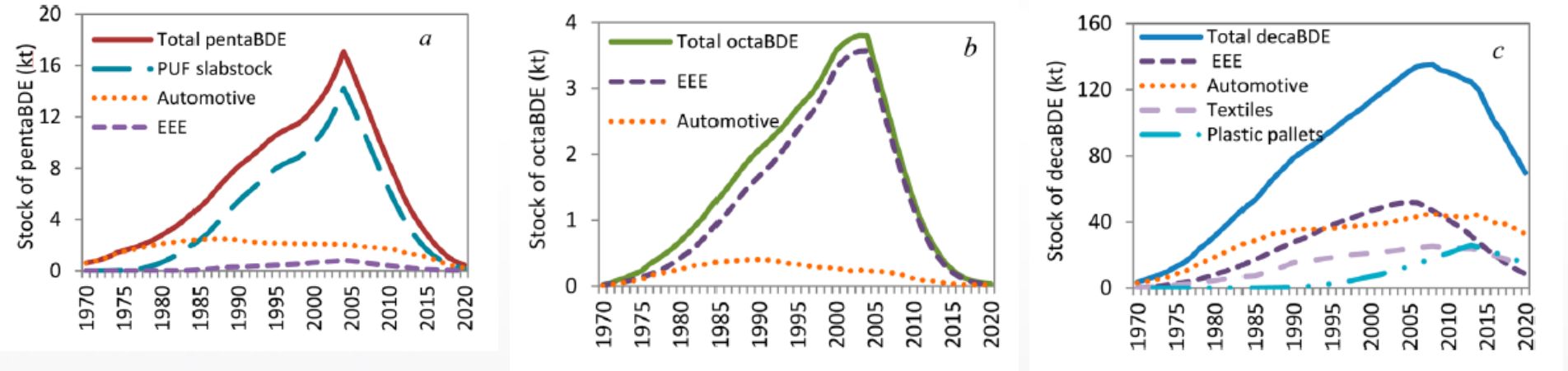


Fig. 6 Estimated in-use deca-BDE stocks in Japan from 2014 to 2040 with case 1 where deca-BDE declines at the same rate as the current rate of decline, and case 2 where deca-BDE is discontinued after 2020

<Fig> Estimated domestic demand and in-stock of PBDEs in Japan (Source: Dien et al., 2017)

3.2 Results and discussion: Use of PBDEs in US and Canada

• In US and Canada, deca-BDE from electronics and automobiles has reached a peak in 2010 and continually decreased over time.
• The total amount of deca-BDE was estimated to be 380,000 ton (35% in automobiles, 35% in electronics, 20% in textiles, and 10% in plastic pellet.

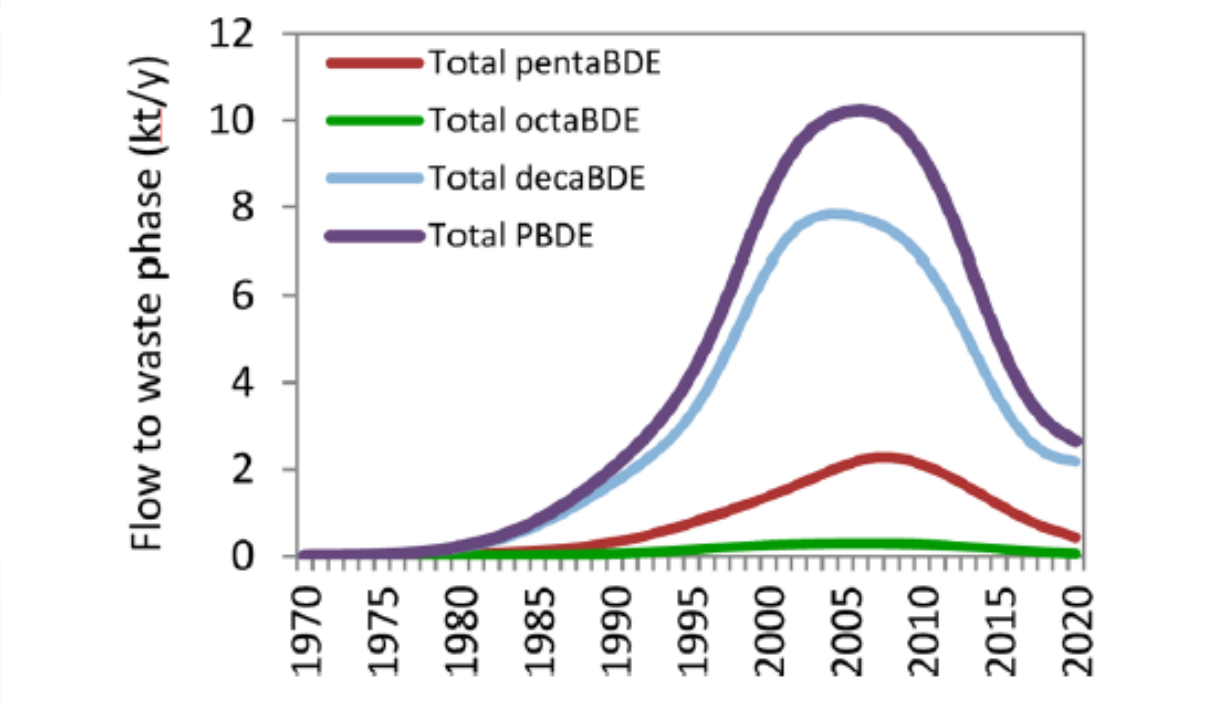


<Fig > Accumulated amount of PBDES in products from use to waste between 1970 and 2020

(Source : Abassi et al., Stocks and Flow of PBDEs in Product from Use to Waste in the U.S. and Canada from 1970 to 2020, 2015, ES&T)

3.2 Results and discussion: Flow of PBDEs to waste phase in US and Canada

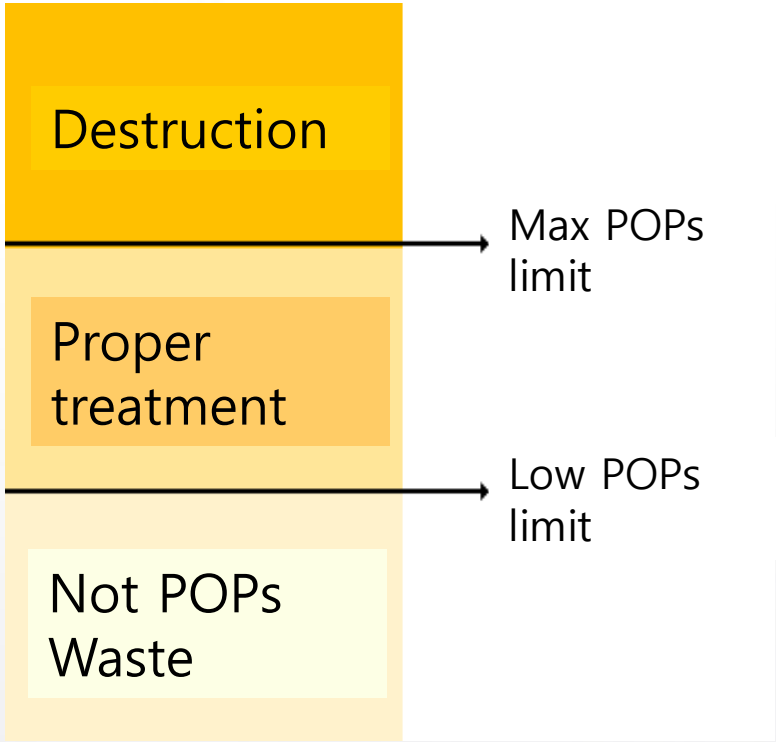
• In US and Canada, the flow of deca-BDE and deca-BDE at waste phase has reached a peak (10,000 PBDEs) in 2010 and then dramatically decreased over time (4~12% annually).



<Fig > Flow of PBDEs to waste phase between 1970 and 2020
(Source : Abassi et al., Stocks and Flow of PBDEs in Product from Use to Waste in the U.S. and Canada from 1970 to 2020, 2015, ES&T)

3.3 Results and discussion: Environmental implications-1

- According to UNEP and EU guideline, more than 1000 mg/kg of PBDEs-containing waste should be chemically destructed
- 100~1000 mg/kg of PBDEs-containing waste should be properly treated without causing contamination
- Less than 100 mg/kg of PBDEs-containing waste can be recycled without limitation



Regulations

> PBDE 1,000 mg/kg
> HBCD 100 mg/kg

>PBDE 100 mg/kg
>HBCD 10 mg/kg

3.3 Results and discussion: Environmental implications-2

- In order to achieve clean cycle of plastics from e-waste, BFRs-containing waste should be properly managed and treated. Otherwise, there is a potential of cross contamination among the recycled plastics, which may cause a concern
- In 2020, by the new regulations in the POPs Act in Korea, more than 1,000 mg/kg of PBDEs is classified as POPs-containing waste and should be properly managed by the hazardous waste treatment guideline in Waste Management Act
- In addition, recycling of such POPs waste will be restricted and prohibited by the POPs Act
- However, existing BFRs in recycled plastics would be a cause of concern in the coming years. The pathways and detailed flow of recycled plastics with BFRS are largely unknown so far.

IV Conclusion and Q/A

Key messages and conclusion

1. As the use of deca-BDE decreases, in-stock and waste phase in electronics also dramatically decreases due to lower amount of CRTs waste stream

2. Among PBDEs, deca-BDE was often found in e-waste streams, especially CRT TVs

3. By 2030, most deca-BDE from e-waste streams diminishes over time and flows into recycled plastics accumulating up to 3,000 ton of BFRs after recycling processes

4. Recycling of PBDEs-containing waste will be restricted and prohibited, but the management of existing PBDEs-containing waste with 1,000 mg/kg could be an important area of concern in the coming years

5. No detailed statistics and flow of recycled plastics with deca-PBDEs are still unknown due to lack of guideline and limited scientific studies

Thank you