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Material Value Chains

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Future Trends in WEEE Composition and Treatment - A Review Report

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Key words: Waste electrical and electronic equipment, product design, manufacturing, electronic industry, consumer electronics

Summary

Currently, electronics is mushrooming in both our leisure and working environment. New wireless applications and equipment enable us to apply electronics in new areas, in which they have not previously been used. In addition, miniaturization and integration make the electronics more and more imperceptible, which opens new doors for end applications to spread in our society. In future, the innovations and developments in the electronic industry are expected to advance even further and more intensively. This will lead, after a delay, to a situation where completely new applications and items, which have not previously been classified as electronic waste (WEEE), enter our recycling system.

This report reviews current trends in consumer behaviour and electronics manufacturing industry to identify possible changes in the future composition of WEEE. In relation to this, a review of the new innovative mechanical recycling technologies is carried out to detect possible treatment methods for the new type of electronic waste. Finally, a short look into legislative aspects within WEEE management is given to highlight possible challenges in the current legislation, posed by the electronics spread all around us.

The study revealed that especially wireless technology together with sensors and monitoring will integrate electronics for instance with clothing, which may generate problems in the recycling stage of the application's lifetime. In addition, the Internet of Things (IoT), as well as the artificial intelligence (AI), will bring new applications under the management of WEEE. Especially AI will however require screens to be realised, which is why displays will be found in the WEEE also in the future.

The technology review identified technologies such as the automatic disassembly, electrodynamic fragmentation and sensor separation, which may partly cope with the future WEEE. The legislative glance noticed that a guidance for the legislative interpretation is required in unclear situations that may be brought out with new applications containing electronics entering in the end-of-life stage. Clarification is required, since the targets and objectives in directives vary, as well as the responsible actor for the waste stream in question.

Helsinki, 31 March 2017

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Abbreviation list

AI	Artificial intelligence
AR	Augmented reality
CCD	Charge-coupled device
CRD	Cognitive robotic dismantling
DE-XRT	Dual Energy X-ray Transmission
EC	Electronic components
EDF	Electrodynamic fragmentation
EEE	Electrical and electronic equipment
ELV	End-of-life vehicle
EoL	End-of-life
EPC	Electronic product code
EPR	Extended producer responsibility
HMD	Head-mounted display
HSI	Hyperspectral imaging
IMSE	Injection-moulded structural electronics
IC	Integrated circuits
IoT	Internet of things
LCD	Liquid crystal display
LIBS	Laser induced breakdown spectroscopy
MDS	Magnetic density separation
MSW	Municipal solid waste
NFC	Near-field communication
NIR	Near infrared
OEM	Original equipment manufacturer
OLED	Organic light-emitting diode
PC	Personal computer

PCB	Printed circuit board
PWB	Printed wiring boards
PSS	Product-service system
PV	Photovoltaic
SMC	Surface mounted components
TFT	Thin film transistor
UAV	Unmanned aerial vehicle
VIS	Visual image spectroscopy
VR	Virtual reality
WEEE	Waste of electrical and electronic equipment
XRF	X-ray Fluorescence

1 Current WEEE streams

1.1 Material flows

When electrical and electronic equipment (EEE) ends its lifetime and becomes waste electrical and electronic equipment (WEEE), it should be collected and handled according to the descriptions in the WEEE directive[1]. The directive has ten categories for different type of equipment for which own collection and recovery rates have been imposed. From 15 August 2018 revised classification to five categories will be applied. During this collection procedure quantities of the collected items/goods should be compiled to the statistics. However, only a part of WEEE ends in statistics. WEEE disappears into other waste streams , such as in the municipal solid waste (MSW), WEEE is hoarded and WEEE is illegally shipped abroad, which is not taken into account in the statistics. Therefore, additional sources for the WEEE quantity estimation should be utilized.

1.1.1 Amount and composition of WEEE

Depending on the source of the data, the worldwide amount of generated WEEE varies between 20-50 Mt whereas for the EU the amount varies from 3.5 to 12 Mt[2–4]. Table 1 presents the amount of EEE put to market and the generated WEEE.

Table 1. Quantities of EEE put to market and WEEE generated in different regions [2–4].

	Unit	Eurostat (2013)		UNEP (2013)		UNU (2015)		
		EU	FI	Global	EU	Global	EU	FI
EEE put on market	kg/ inhabitant		23.1			8.2*	19.4*	25.4*
	total Mton	8.2	0.126			56.5*	9.8*	0.138*
E-waste generated	kg/ inhabitant		12.1			5.9**	18.7**	21.5**
	total Mton	3.5	0.066	20-50	12	41.8**	9.5**	0.118**

* Presenting the situation in 2012
** Presenting the situation in 2014

When comparing the amount of EEE put on the market with the amount of waste generated, it can be noticed that the amount on the market is larger than the generated waste amount even with the estimates. This indicates a growth in the waste amount in the future. It also indicates significant losses in the WEEE statistics. In literature the growth has been reported to be around 4% annually[3].

From Table 1 it can also be noticed that the statistics from Eurostat corresponds to the other studies rather well when we look at the numbers of EEE put on the market. On the other hand, if we look at the WEEE generated, it can be seen that the numbers from Eurostat are significantly smaller than those presented in other studies. It has been reported that only roughly 35% of generated WEEE ends in statistics, while the rest remains unreported[5]. A schematic description of WEEE flow in Europe has been presented in Figure 1.

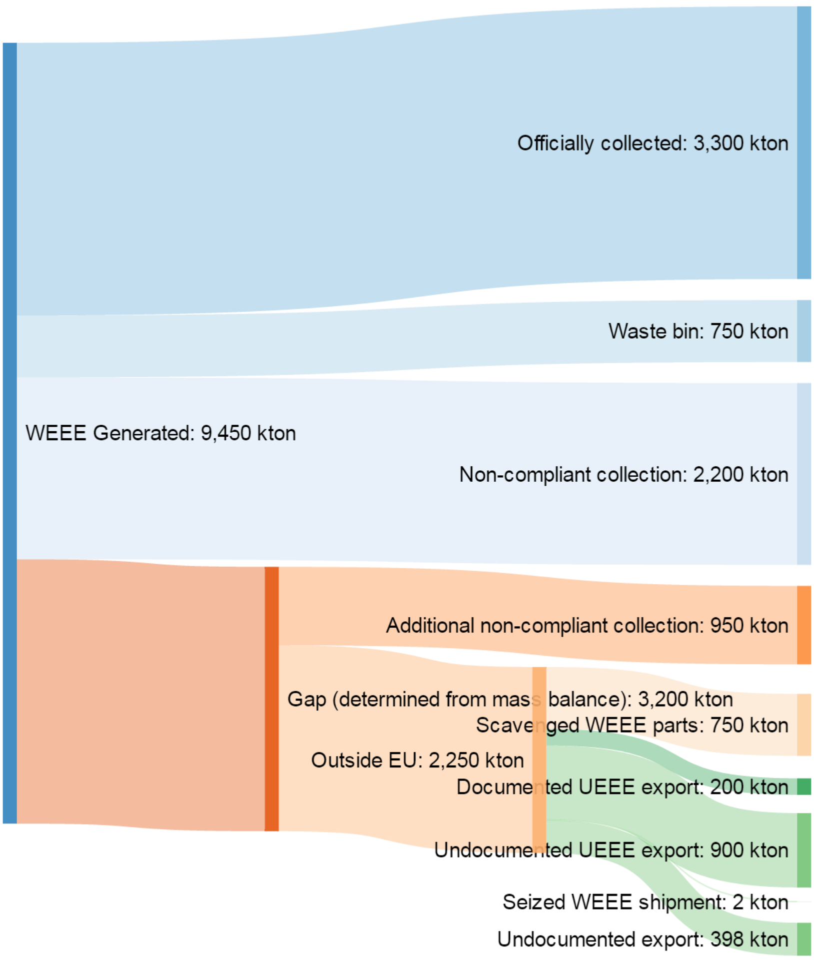

Figure 1. The 2012 WEEE waste flows in EU. Derived from [6].

In Figure 1 we can see that a significant share of total generated WEEE (9,450 kton) is either shipped out from Europe (2,250 kton) or ends in other waste streams (750 kton) or in treatment within Europe which is not monitored (2,200 kton + 950 kton). This leads to losses of potential material to be recovered.

The officially collected share (3,300 kton) in Figure 1 can be further divided according to the statistical application categories determined by Eurostat. The application distribution of the officially collected amount of WEEE for both 2012 and 2014 has been presented in Figure 2. Even though this doesn't represent the entire WEEE application distribution, it gives an indication of how effectively different applications are collected.

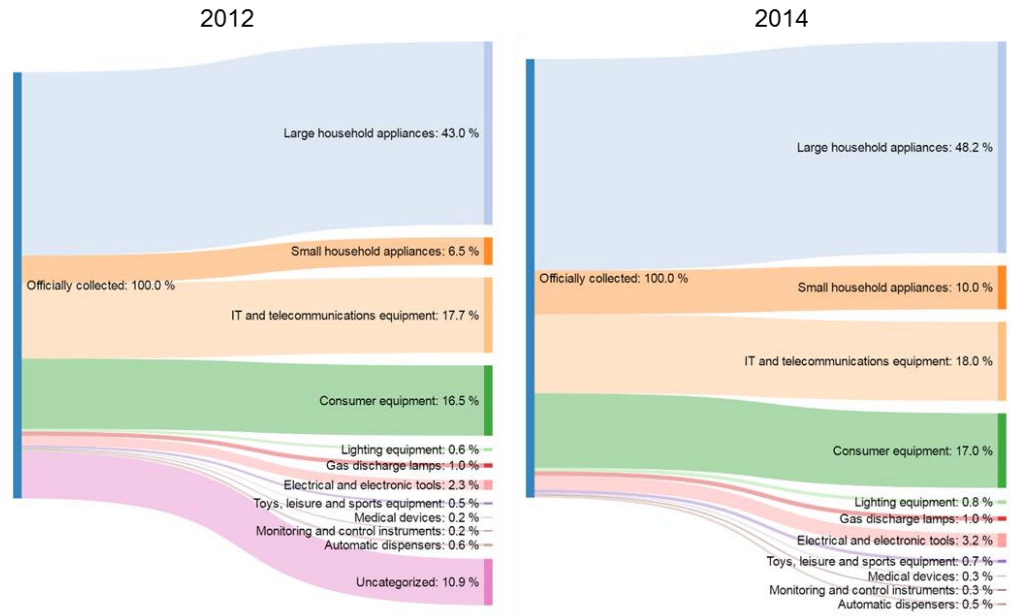

Figure 2. Application mass distribution of officially collected WEEE in Europe 2012 and 2014. [2]

By looking at Figure 2 it can be noticed that a major share of the collected WEEE composes of large household appliances. Other significant application categories are IT and telecommunication equipment, consumer equipment and small household appliances. Since the statistics are based on weight, large household appliances which are heavy, generate easily a large share of the total amount. In addition, especially small appliances have been reported to end up in municipal waste bins which decreases their share in the official collected data, and further on increases the share of large appliances[6].

There is no great difference between 2012 and 2014 except in the share of uncategorized appliances, which in 2012 was around 10%, while in 2014 it was 0%. However, statistical variations may have affected this.

If the shares in Figure 2 were plotted in terms of the value of the collected WEEE, IT and telecommunication equipment and consumer equipment categories would become more significant due to the applications such as mobile phones and laptops, which contain valuable precious metals[3,7].

The composition of WEEE, due to the vast range of different equipment and appliances, is truly heterogeneous with significant variations. Therefore, a detailed material composition analysis of the entire waste stream is difficult to do. However, some studies of different product groups have been carried out. The results of one such study are presented in Figure 3.

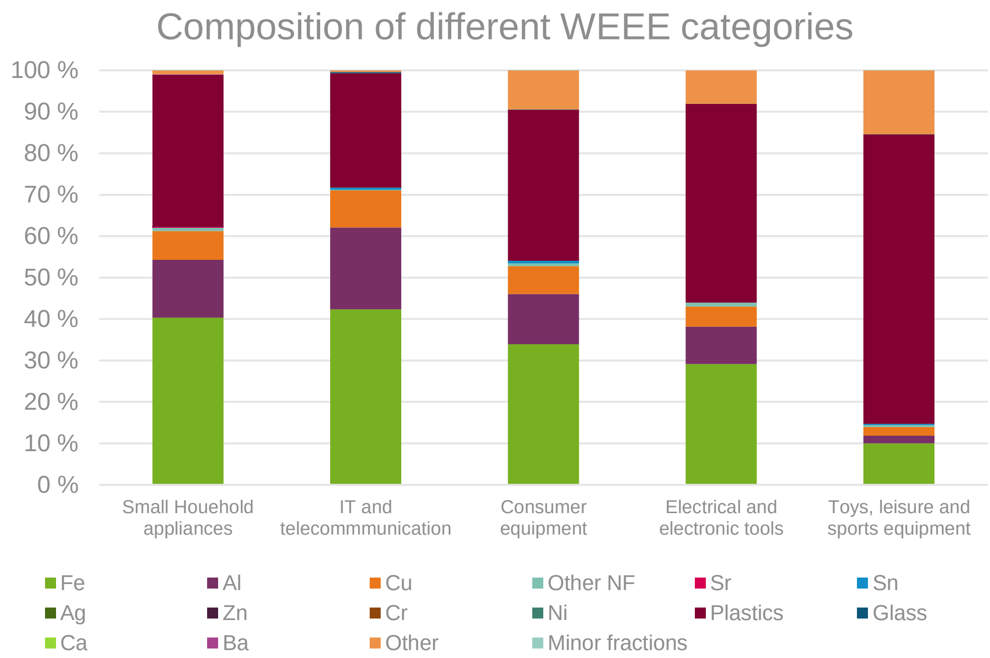

Figure 3. Material composition of five different WEEE equipment categories. Derived from [8].

WEEE composes mainly of plastics and metals. Most common metals are iron, aluminium and copper. However, in value, precious metals such as gold, silver and palladium generate largest shares of the equipment. Plastics are used in several components of electrical equipment such as in the casing and in the printed circuit board as resin[3,9]. The types of plastics in the equipment categories vary quite remarkably. Different types of plastic found within the WEEE equipment categories are presented in Figure 4.

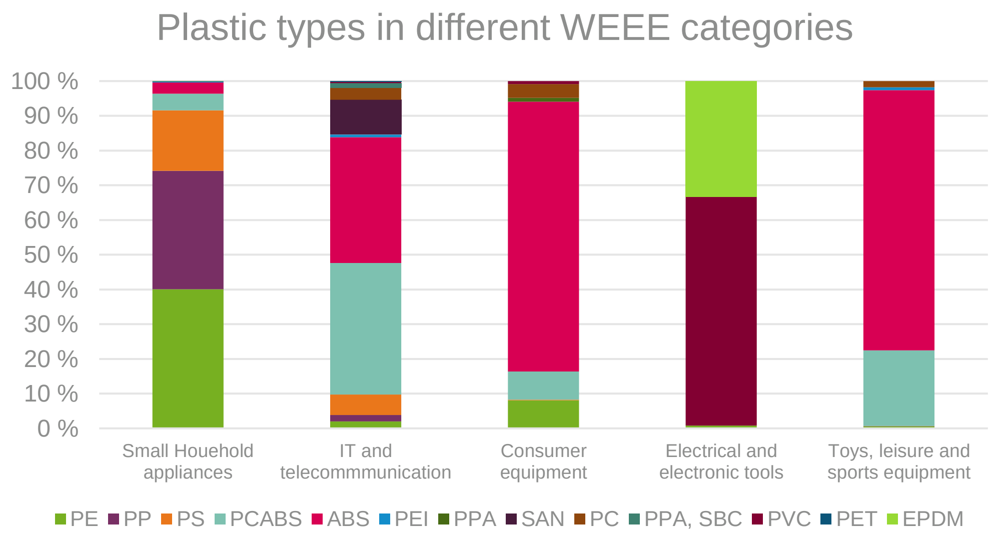

Figure 4. Plastic types in different WEEE equipment categories. Derived from [8].

Several kinds of plastics are used in different EEE which makes their separation challenging. Beside the large number of plastic types within a WEEE equipment category, categories differ significantly from each other. Therefore, these categories should be treated separately, in order to minimize the mixing of even more plastic types with each other.

1.1.2 Other waste streams interconnected with WEEE

Although batteries are not in the same waste category as WEEE, the presence of batteries in WEEE is increasing mainly due to the increasing mobility features of EEE, and to expanded markets and volumes of certain mobile products. Also the trends such as the IoT (Internet of Things) incorporates new items into the WEEE stream, some including batteries for mobility. Therefore, batteries are lightly discussed throughout the report.

The amount of collected battery waste available for recycling is small and does not match the amount of batteries put on the market annually, as seen in Table 2. The Directive on Batteries and Accumulators (2006/66/EC) sets the following minimum requirements: 45% collection rate by 26th September 2016, and 50% recycling efficiency by average weight of waste batteries. Batteries that are collected together with WEEE should be removed, after which they are subject to the requirements of the battery directive.

Table 2. Sales and collection of portable batteries and accumulators in Europe (EU28 -Greece +Norway +Lichtenstein) and in Finland.[10]

Year	Europe		Finland	
	Products put on the market [t]	Waste collected [t]	Products put on the market [t]	Waste collected [t]
2009	195 464	46 891	2 569	1 039
2010	219 336	58 034	2 814	877
2011	213 171	67 844	2 763	968
2012	209 685	74 637	2 752	920
2013	203 493	76 397	2 703	1 127
2014	187 342	73 949	2 651	1 252

In 2012, the EU collection rate of all portable batteries was about 35%. The collection rates of rechargeable batteries tend to be lower than those of non-rechargeable. For example, in Germany the collection rate of non-rechargeable batteries in 2012 was 53%, and that of rechargeable batteries 24%. This may result from the long lifetime of the rechargeable batteries (4-7 years), integration of batteries in the devices, or from the behaviour of the end-users who may hoard spent batteries at homes for another 2-4 years before disposing them. Also, the collection may be inefficient and recycling rates low due to the insufficient implementation of legislation, and lack of public awareness.[11]

Different manufactures produce batteries with variable components, which is why the stream of used batteries is heterogeneous in terms of materials. In Li-ion and NiMH batteries valuable and/or harmful components are tightly enclosed within the battery case, which is usually made of steel, aluminium, plastic or nickel alloys.[12]

Electrical equipment and components are widely used also in automotive industry and other transport vehicles, such as trucks, buses, electric bikes, boats, and airplanes. Several systems such as safety, infotainment and vehicle communication rely on electronics in new cars[13]. These systems utilize components such as microcontrollers (electronic control units), sensors, actuators and data buses[13]. In addition, screens and different electrical motors are used more and more in the automotive industry[14]. It has been reported that the electronic content in vehicles will continue to increase in upcoming years, likely at an increasing rate. This increase will rely especially on electronic applications (such as navigation and infotainment), however in addition, items that were formerly mechanical will continue to become electronic. Within the next five years, personalization of the driver's experience will also increase, mirroring the popularity of social networking applications and the ability to get information and entertainment instantaneously.[13] Electronic technologies that have replaced traditional technology is presented in Table 3.

Table 3. Electrical technologies that have replaced traditional ones in a car[14].

Current technology	Replaced technology
Passive components (switches, capacitors, inductors etc.)	Active controller area network bus components (sensors, microprocessors)
Starters	Start-stop starters (electronically controlled)
Alternators	Combined generator/motor
Combustion engine	Electrical motor
Engine valves	Electrical variable valves
Hydraulic power steering	Electrical power steering
Mechanical pumps	Electrical pumps
Mechanical fuel injection	Electrically controlled fuel injection
Mechanical turbochargers	Electronically controlled turbochargers
Brake vacuum booster	Electro-hydraulic booster
Brake master cylinder	Electrical braking cylinder
Handbrake	Electrical calliper
Manual gearbox	Electrically actuated gearbox
Shock absorbers	Electronically controlled shock absorbers
Automatic transmissions	Electronically controlled transmissions
Lead battery	AGM battery / Lithium battery
12 Volts	48 Volt systems

Furthermore, in the next 10 years, the electronic architecture of vehicles will become more consolidated in order to sustain the increase of the electronic content. The trends in vehicle electronics are presented in Figure 5 and Figure 6.

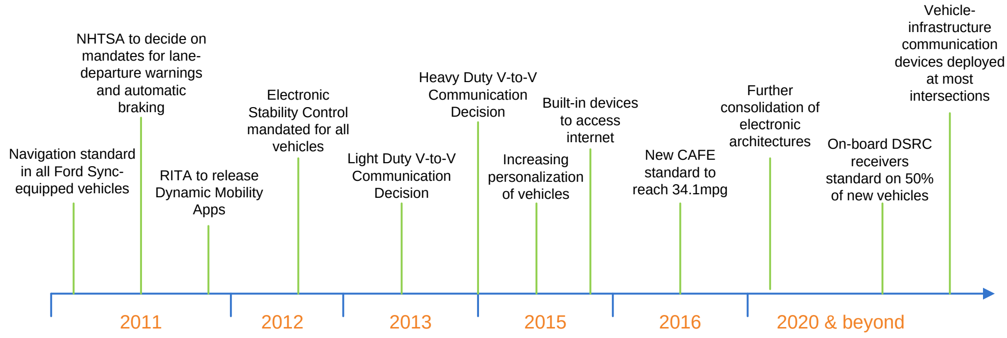

Figure 5. Timeline for notable milestones in vehicle electronics. (Derived from [13].)

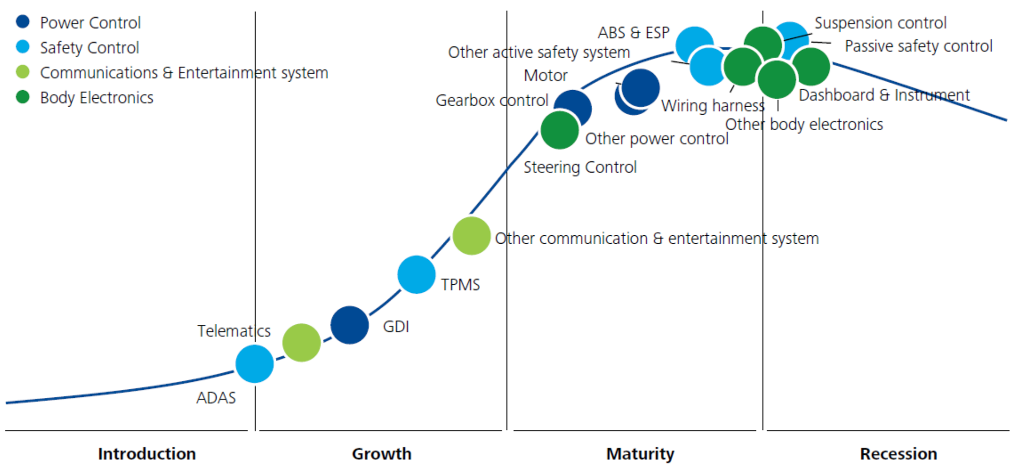

Figure 6. Life cycles of automotive electronics segment[15].

When a vehicle cannot be used anymore and there is no economic value to maintain it as a vehicle, it becomes end-of-life vehicle (ELV) and is deregistered. After this the ELV enters the recycling value chain where metals, plastics, rubber, liquids, batteries and tyres are separated for further treatment. In this treatment the electronics end up usually in either the metal fraction or the organic fraction. The share of electronics in various vehicles is presented in Table 4.

Table 4. Composition of ELVs by some manufacturers. (Derived from [16].)

Material	Daimler (%)	Volkswagen (%)	Ford (%)	Fiat-Chrysler (%)	Nissan (%)
Ferrous metals	46.9	59.0	76	63	59.4
Non-ferrous metals	24.3	12.0		10	14.1
Plastics	21.1	19.8	18	13	13
Fluids		4.7	0.8	5	
Electronics	0.2	0.2	0.2		
Other	7.5	4.4	5	9	13.5

It can be noticed that the share of the electronics presents rather small part of the total amount. However, when the amount is proportioned against the mass of a vehicle, it can be estimated that roughly 5-10 kg of electronics per vehicle can be found. In some studies the share has been estimated to be as high as 7.5 w% which would lead to roughly 90 kg of electronics per vehicle[17]. The various definition of electronics in the studies partly explains the significant fluctuation.

According to Eurostat roughly 6.5 million tonnes of ELVs were generated in Europe in 2014[18]. If we use 0.2 w% as a rough estimate for the share of electronics in a car, it can be assumed that about 13 000 tonnes of electronics end up in the ELV waste. On the other hand, if we use the electronics proportion presented by Yamasue (7.5 w%)[17], the amount rises to 487 500 tonnes which is a rather significant amount.

1.2 Life cycles and forecasts

One specific nature of WEEE is its dynamism which originates from the variations in the lifecycle of different electronic equipment. Several reasons cause the variations. Lifecycles of various EEE are presented in Figure 7.

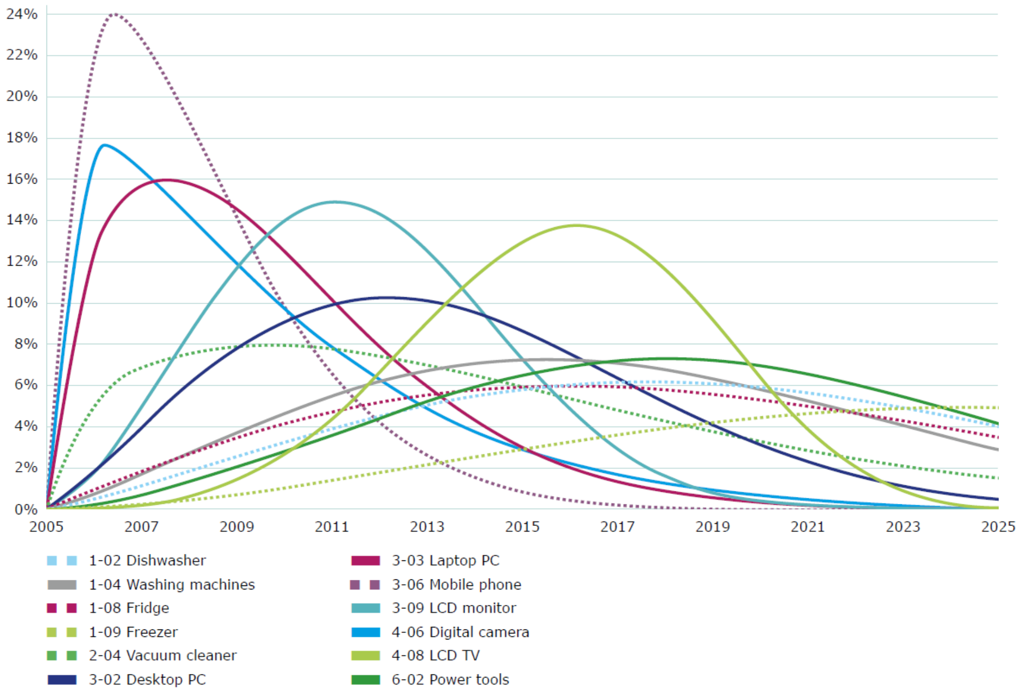

Figure 7. Various product lifespans. The graph illustrates what percentage of new products placed on the market in 2005 is becoming obsolete in the following years. [19]

It can be seen that the variations in the lifecycles are significant. For example, mobile phones, digital cameras and laptops have remarkable shorter lifecycle than freezers, fridges and washing machines. This is caused by several reasons such as the size of the equipment, model regeneration and durability.

In general, the lifespan of applications and equipment has shortened during the last decade, see a listing of certain categories in the blue box on the right. The decrease in the residence time has targeted especially the appliances which already have a rather short lifespan. This escalates the WEEE composition dynamism and moves the curves to the left, even closer to the y-axis in Figure 7.

Decline in the residence time of different applications put on the market in 2000 versus 2010.[19]

- 17% for screens
- 12% for small household appliances
- 10% for IT and telecom appliances
- 10% for lamps
- 7% for large household appliances
- 4% for cooling and freezing
- 4% for professional appliances

Together with the increase in the number of product items per household or per person, the amount of EEE and WEEE is expected to increase. Of course factors such as the amount of materials per product will restrain the total amount in tons of generated WEEE. On the other hand, as an example from Netherlands a net stabilisation of the EEE put to market amounting to about 26-28 kg/inh since 2003 has been observed even though the number of product items has increased[19].

2 Consumer trends

The formation of consumer technology trends can be considered as a complex process, where the advancements in material research, software development and the creation of novel technological systems, such as the Internet of Things, enabled by both advanced hardware and software, affect each other.

In this chapter the consumer trends are observed from the applications' perspective: more precisely, how each category of new applications affects the WEEE stream. The new devices appearing on the market are divided in this chapter according to whether they replace an existing device or they are an answer to a completely new need of the consumers. In addition, there is a case that falls between the two cases mentioned above; the devices with new or improved functionalities that nevertheless do not replace the old device they resemble, but supplement them. This is a simplified and time-depended categorisation, but it is a suitable means to organise the constantly expanding offering of consumer electronics in this review.

Completely new and supplementing applications can be assumed to increase the stream of WEEE, whereas the effect of appliances replacing existing applications is unclear: there are cases where they may even reduce the amount of WEEE per volume or weight, but it is safest to assume that at least they don't increase the amount of WEEE as much as the two other types of applications. The amount of formed WEEE at a certain time is depending on other factors as well, such as the devices' lifespan, which was discussed in the previous chapter.

In addition to the new applications entering the market, energy harvesting and storage from the consumers' perspective are shortly discussed at the end of the chapter.

The above-described categorization of the devices released on the market is illustrated in Figure 8. It is used as a basis for the organization of this chapter. The listing of the technology trends and applications is not all-inclusive, but gives a general overview on the current situation in 2016.

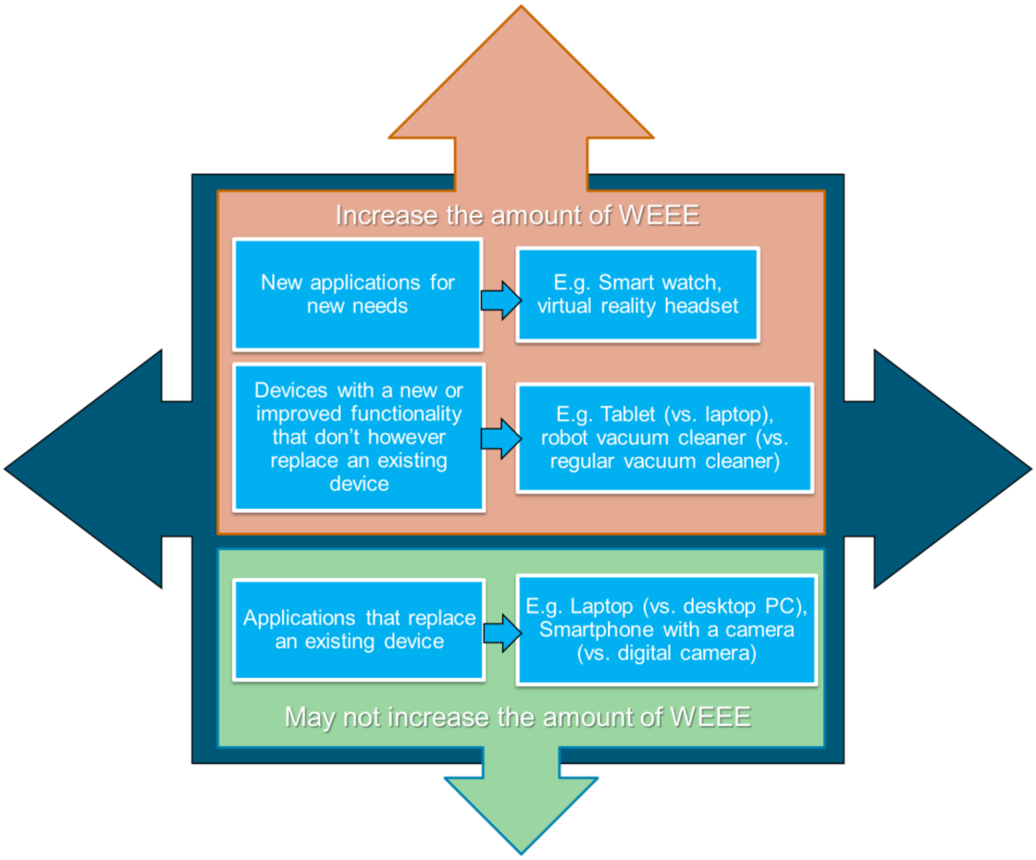

Figure 8. Categorization of the devices released on the market based on how they affect the amount of WEEE.

2.1 Applications and systems for new needs

2.1.1 IoT - Internet of Things

Objects in a daily life can be equipped with identifiers and wireless connectivity, enabling them to communicate with each other and be managed online. This system is called the Internet of Things (IoT).[20]

Electronics companies are building wireless connectivity into a wide range of devices. Mobile data coverage has increased, battery technology has improved, and solar recharging has been built into numerous devices. This enables billions of objects connecting to the network within a few years.[20] It has been predicted that over 50 billion devices will be connected by 2020[21].

Figure 9. An elucidation of IoT. Any object equipped with a connectivity device can be connected to the IoT. (Image from Pixabay, public domain)

In the past, people communicated with people and with machines. IoT-enabled objects will share information with people, software systems and other machines. The IoT will connect everything from industrial equipment to everyday objects. Wearable computing and digital health devices can also connect people to the IoT landscape. Basically anything to which a sensor and a connectivity device can be attached can participate in the connected ecosystems.[20]

Increased connectivity due to the IoT can be assumed to increase WEEE volumes as some of the previous traditional household waste will be defined as WEEE due to the attached sensors and/or connectivity devices. This includes both an increase in volumes of electronic components as well as in waste volumes due to transfer of certain waste from household waste to WEEE categories. It can be predicted that the IoT will lead to an increase specifically in circuit boards, batteries, connectivity devices and sensors.

2.1.2 Artificial intelligence

Artificial intelligence (AI) is intelligence exhibited by computers. With AI, machines can perform tasks that have normally been done by people - because so far only humans have been able to do them. Current examples of the use of AI are conversational assistants that have been released by Apple, Google and Microsoft.[22] With a conversational assistant the user can command the device by voice.

For consumers, artificial intelligence will continue to be incorporated into technology products, services and software in 2016, but AI will find its way into robots as well. A French robotics company is expected to begin selling a social robot in 2016 that is claimed to be able to interact with people. However, it is suspected that it will take another few years until robots in general begin filling personal roles, such as babysitting.[23]

As AI has so far been exploited mainly in software applications, its effect on WEEE is rather limited at the moment. In future, AI will be used increasingly in smart home and robot applications, meaning the growth in number of sensors, batteries, and data processors to be found in WEEE. Domestic service robots are covered in section 2.3.2.

2.1.3 Virtual and augmented reality

Virtual reality (VR) can be defined as a three-dimensional environment that is entirely computer generated. Augmented reality (AR) or mixed reality, on the other hand, means that the virtual graphics are superimposed over a real-world environment.[24,25] The user can explore and interact with the environment for example through a head-mounted display (HMD), as shown in Figure 10. Many companies have released their first HMDs on market in 2016.[26]

Figure 10. Head-mounted display (HDM) used for a VR experience. (Image from Pixabay, public domain)

An AR device can also be a tablet or a smartphone using a specific application. The device's screen displays a view where the digital information is combined with the physical world around the user, as captured by the device's camera. This is illustrated in Figure 11. First applications are on the market.[26]

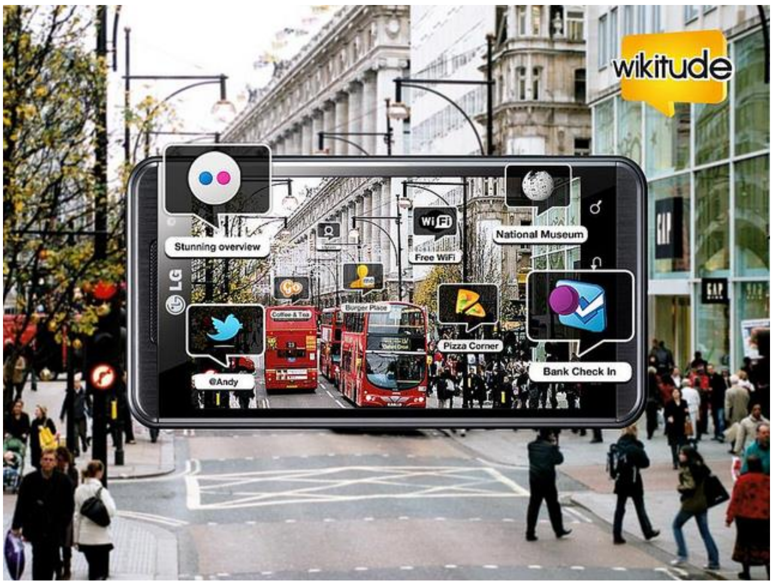

Figure 11. Using a mobile application for an AR immersion. (Image courtesy of LG via Flickr)

The market for HMDs is expected to grow significantly during the next years. Also the HMD technology is assumed to improve drastically over the next five years. Figure 12 shows Gartner's forecast for the sales of HMDs through 2020. The consumers are expected to rapidly adopt HMDs, with video games being the first popular HMD application type.[26]

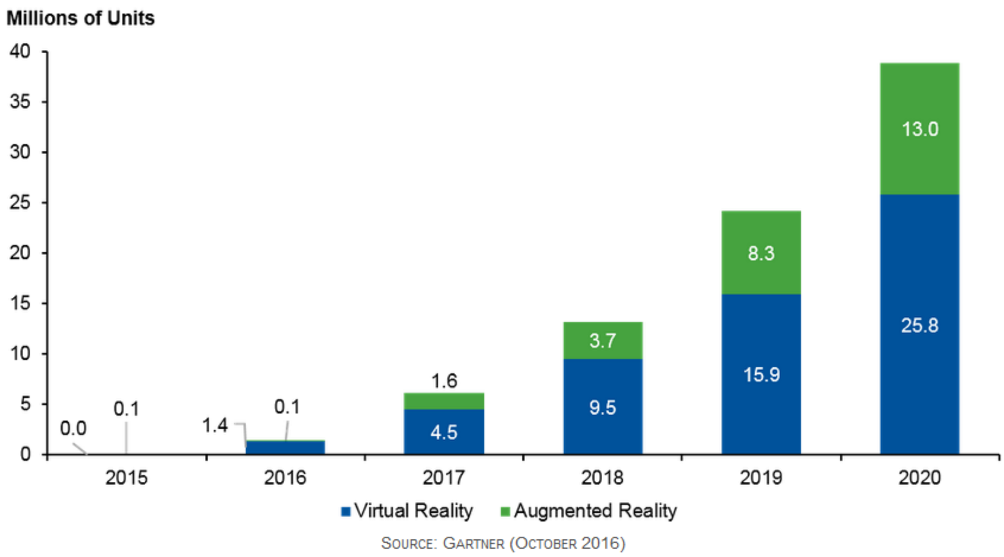

Figure 12. Gartner's forecast for the sales of head-mounted displays (HMD) related to the virtual/augmented reality applications.[26]

At the moment, VR and AR applications are rather separate from other applications and devices. However, in future the VR and AR will be integrated with multiple mobile, wearable, IoT and sensor-rich environments and this will extend the single-person experience to environments, where entire rooms and spaces are connected to virtual worlds.[26]

Transparent electronics is a technology strongly linked with AR and VR. It is based on materials in which a high level of optical transparency and an optimal conductivity are combined. Innovations in this field are expected to enable see-through futuristic applications. The essential building blocks of transparent electronics are transparent thin film transistors (TFTs).[27] Virtually all flat-screen TVs and smartphones exploit TFTs today; they are the basis of currently used display technologies: liquid crystal displays (LCDs) and organic light-emitting diodes (OLEDs).[27,28]

Figure 13. An array of flexible, transparent TFTs developed at Argonne National Laboratory. (Mark Lopez/Argonne National Laboratory)

In addition to the use in AR and VR glasses, the future applications of transparent displays include, for example, a normal window that doubles as a screen when turned on. The next step is adding logic and memory to the films, so instead of a plain screen an entire flexible and transparent TV or computer can be produced.[28]

Flexibility is another desired feature in displays. Combining flexibility and transparency enables skin-like thin flexible devices that can be used for wearable displays[29]. Wearables are discussed in the next section.

In the first stage, the use of VR and AR will lead to an increase of all sorts of display units in WEEE. Later on the use of the technology will also raise the number of wearables, sensors and other mobile and wireless technology among consumers, meaning the growth of batteries and connectivity devices found in WEEE.

2.1.4 Sensors and wearables

Sensors are not new components in consumer electronics, but due to their recent development in size and cost reduction, together with increased power efficiency, new applications have been made possible in the fields of home automation, robotics and digital health. Sensors for movement, proximity, temperature, pressure, flow, acoustics and imaging, among others, are used in applications such as portable devices, gaming, navigation, and home appliances.[30,31]

Advances in sensor technology have enabled new applications especially in wearables[30]. Wearable technology means clothing and accessories in which advanced electronics are embedded. They can provide sensory and scanning features not typically seen in common hand-held devices, such as monitoring the user's physiological functions.[32] The field is strongly connected to the IoT[33].

Today the most popular wearables are fitness trackers and smartwatches[33], see Figure 14. The difference between the two is that fitness trackers only monitor the user's health and activity, while a smartwatch is a more sophisticated device enabling also features such as communication and personal organiser - similar features to those of a smartphone[34].

Figure 14. Left: Activity wristbands (Image courtesy of US CPSC via Flickr), right: a smartwatch (Image from Pixabay, public domain)

Other wearables include eyewear, which are projected to have their highest market potential in industry, however some hardware providers are expected to also offer consumer-friendly options. In addition, wearable technology is finding its way into clothing as traditional fashion and fitness brands are combining their forces with conventional technology companies in order to develop smart clothing. Prototypes of shoes and belts have already been revealed. Other products comprise clip-on devices, hearables, and helmets, to name a few.[33] The realised and predicted shipments of these segments are illustrated in the following figure.

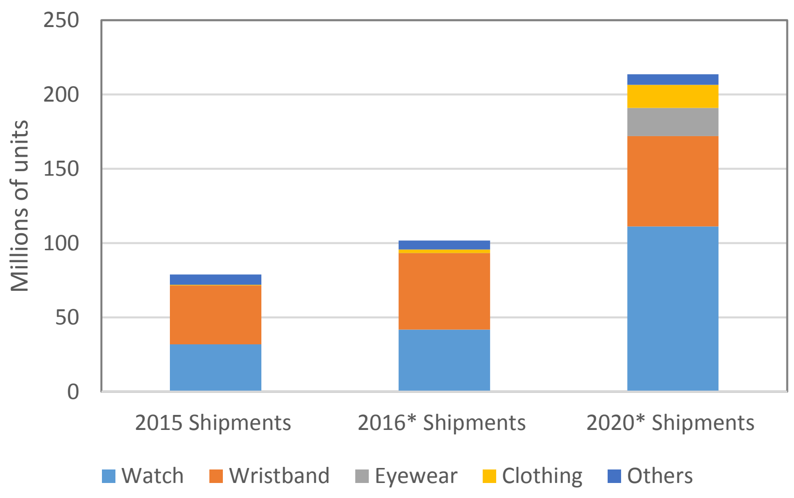

Figure 15. Shipments of wearables by category, millions of units. Numbers for 2016 and 2020 are predictions.[33]

Instead of tracking the user's physiological functions, wearables can also monitor the environmental parameters such as air quality or presence of volatile organic compounds. These devices are expected to enter the market in the next two years.[35]

Essential parts of wearables are batteries, sensors, data processors and connectivity devices (Bluetooth, NFC, Wifi, Zigbee)[36], of which increased presence in WEEE is expected.

2.1.5 Radio-frequency identification (RFID)

Radio frequency identification can be defined as an automatic identification technology which uses radio-frequency electromagnetic fields to identify objects. The identification is performed by a reader when the object carrying an RFID tag arrives within its reading distance.[37] The technology is already employed in many application areas, such as in contactless payments[38], access management, tracking of goods, persons and animals, toll collection, and machine readable documents, to name a few[39]. In addition, an RFID can be attached to a sensor, and the sensor data can be read from the RFID tag[40], such as in Figure 16.

Figure 16. VTT has developed a sensor that detects food spoilage inside a package. The sensor layer is part of an RFID tag, and the sensor data can be read wirelessly using an RFID reader in, for example, a smartphone.[41] This is an example of a food product containing EEE. (Photo credit: VTT)

RFID tags generally comprise of an electronic chip to store the information, and an antenna to pass the information to the reader[37]. They come in many different sizes and shapes, e.g. in the form of coins, as glass tube transponders, integrated into mechanical keys, as part of wristwatches, and as paper thin transponders. Depending on the functions and uses of RFID, the attachable material and the type of environment in which RFID is expected to function, will determine the frequency of operation, the source of the power, but also the design for the length of life.[42]

Tags can be classified based on the power supply to passive, semi-passive and active tags. Passive tags have no power of their own, and hence only work when supplied with the radio signal from the reader. Semi-active tags are battery assisted tags, which enables the tag to function independently, although they do not have active transmitters. Active tags have their own power source (battery or an active transmitter) which allows a greater read-and-write range.[42]

Another relevant classification of RFID is the division to read-only and read-write tags. Read-only tags contain a non-changeable programmed identifier that remains during the chip's life. Generally, these tags are inexpensive but cannot be reused and can only store a limited amount of data[42]. Read-write tags are more sophisticated and expensive due to the possibility of reprogramming the tags with new information, which means that the tag can be erased and reused. In addition, read-write tags may store and process information locally, which is valuable when dealing with high-volume, complex supply chain applications. Typical features of passive and active RFID tags are presented in Table 5.

Table 5. Comparison of some typical features of both passive and active RFID tags. (derived from [42])

Feature	Passive	Active
Size and weight	Small (or thin)	Large
Cost	4 cent to <1 €	3 € to a <100 €
Life	Virtually unlimited	3 to 7 years
Range	Up to 30 meters	Up to 30 meters
Reliability	Excellent	Good
Sensor input	Little or none	Any
Can emit continuous signal	No	Yes
Area monitoring/geofencing	Rarely	Yes
Multi-tag reading	Fair or none	Excellent (e.g., thousands)
Location using a beam	Yes, but only short distance	Yes, at long distance
High-speed reading	Fair	Excellent
Data retention	Small to medium (e.g., 1 Kbit)	Medium to high (e.g., 1 Mbit)
Very slow signal power	No	Yes – no need to get the signal and back because semi-active and fully active tags emit their own signal and the battery boosts it
Security features of signal and processing	Limited	Excellent
Event signalling	No	Yes
Electronic manifest	No	Yes
Data logging	No	Yes

The quantity of RFID in products is increasing drastically as can be seen from Figure 17. Passive RFID tags are generated in multifold quantities compared to active ones. One reason for this is the average price of the tag, which for an active tag is significantly higher. The increase in quantity somewhat follows the decreasing trend of an average price. In the future, the RFID tags will be the key components of the digitized world and will be linked to emerging technologies such as the IoT and AR[43,44]. In addition to consumer products, RFID technology can be utilized in recycling technology, which will be described in section 4.1.

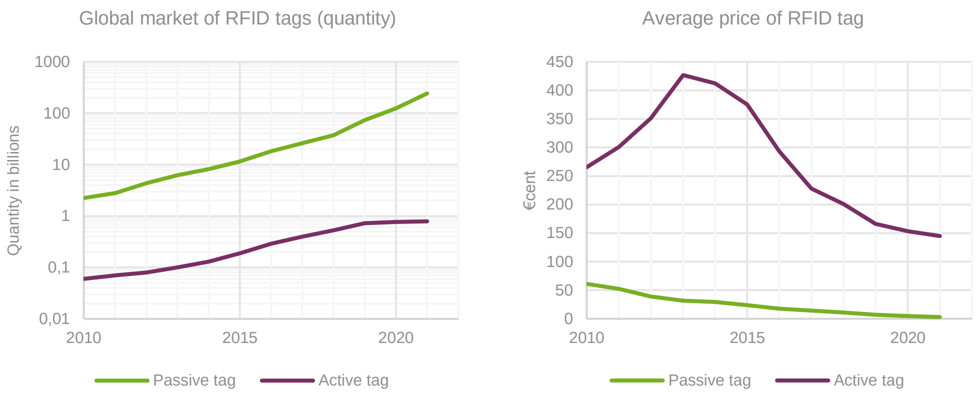

Figure 17. Global market in quantity and average price of a both RFID tag technologies. (Derived from [42])

2.1.6 Home appliances for specific purposes

There is a wide variety of kitchen appliances that are designed for only one or for very limited purposes. Common to these devices is that they do the chores that could often be done by using the fitted kitchen appliances such as (gas) stoves, electric ovens or freezers, which are already found in almost every home. The use of the automatic kitchen appliances is however often justified by the ease of use[45], the quality of the result[46] or energy-savings[47].

The devices that have attracted more attention in recent years include for example single-serving coffee brewing machines, espresso machines, electric cooker pots, yogurt makers, ice cream makers, sous vide circulators and various food preservation equipment.

Especially the single-serving coffee brewing machines, or capsule coffee makers, have gained attention due to their rapidly increased popularity and because of the large amount of waste - the coffee capsules - they create[48]. 2013 was the first year when the sales of the capsule coffee makers exceeded the sales of the conventional drip coffee makers in the Western Europe, reaching almost 10 million units[49]. In 2016, 17 % of the British owned a capsule coffee maker, and other 19 % were interested in buying one[48].

It can be estimated that the sales numbers of these kind of single-purpose devices often decline and remain low after the record figure years. This is why their effect on WEEE composition and volume is expected to be minor in the long term.

2.1.7 Electrified devices

Electrified devices, in this context, are gadgets that try to replace products that originally did not contain any electronics. Examples of such devices are e-readers, electric bicycles, electric tools, electric toothbrushes, electric skateboards, electrified kitchenware (electric pepper mill, electric knife), electric blanket, electric lighters, and electric lights mimicking candles and oil lamps. Electric bicycles fall under the new WEEE legislation.

It is clear that these types of devices increase the WEEE, but the effect can be estimated to be quite marginal due to their assumable low sales numbers and small size. The only exception seems to be electric bicycles. It was estimated in 2011 that the sales of electric bikes in Europe would exceed 1,8 million units in 2013. In the same time, it was also projected that the worldwide sales would reach 40 million units in 2015, China being the largest market.[50]

2.1.8 Gadgets for leisure activities

These gadgets have been introduced to the market during the past few years and they are made for leisure activities. Such devices are personal drones, or unmanned aerial vehicles (UAVs), see Figure 18, which are currently mostly used for aerial photography and video shooting[51]. It has been estimated that the sales of drones will increase from 2.5 million units in 2016 to 7 million units in 2020 in the U.S.[52]

Another example of a device in this category is a self-balancing scooter, or a hoverboard, see again Figure 18. It is used as a challenging but entertaining means of personal transportation in short distances[53]. Over 2,5 million gadgets were sold in the U.S. in 2015.[54] The device is however suspected to be a passing fad[53], and will probably be replaced by some other type of electric means of transportation as a new trend arises.

Figure 18. Left: Camera drone (Photo credit: Pixabay), Right: 2-wheel self-balancing scooter, or hoverboard (Image courtesy of www.soarboards.com via Flickr)

2.2 Applications replacing existing devices

Replacing an existing device does not always mean that the replaced device ends up recycled in a short time scale, because people tend to save the replaced devices in their homes instead of getting them recycled. However, the applications presented in this section are devices that are purchased for replacing other types of applications.

2.2.1 Applications with increased mobility

Mobility is one of the key demands for electronics posed by the consumers[55]. When the mobility of a computing device is increased, the device is made lighter, thinner and cordless, which means that the computing power is compromised. However, at the same time each mobile device generation is more capable and more powerful than the preceding generation, according to Moore's law. At some point the performance of the lighter and more mobile gadget reaches a level that is sufficient for every-day tasks for an average consumer.[56]

In 2008 the worldwide sales numbers of laptops, or notebooks, surpassed those of desktop computers[57]. Besides being replaced by laptops, another factor affecting this is the increased lifetime of computers: When the computing power reaches a certain level, it is sufficient also for the future applications and operator systems and there is no need to buy a new computer every time a new operator system is launched.[56] One prediction of the worldwide shipments of desktop and laptop computers is illustrated in the following figure.

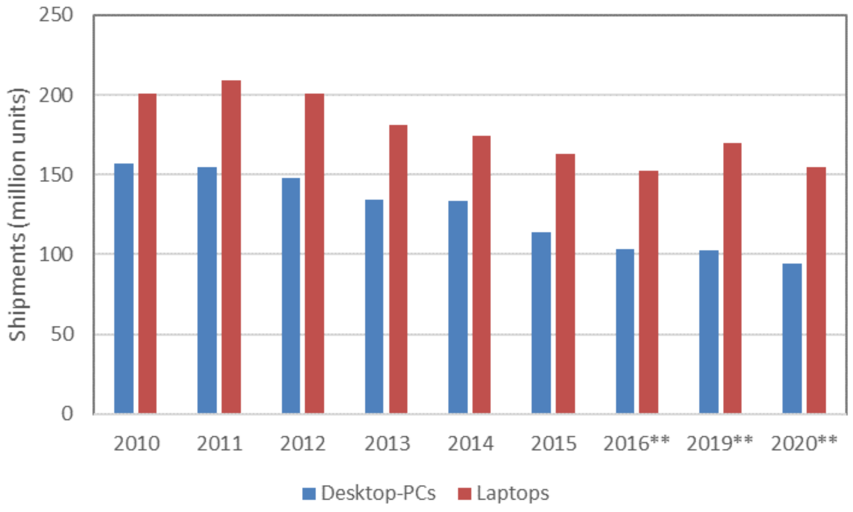

Figure 19. Realised and predicted(**) desktop and laptop computer sales worldwide in millions of units.[58]

The situation with tablets and smartphones in relation to each other or to personal computers (PCs, including desktop and laptop computers) is disputable. Some suggest that tablets and smartphones will soon replace PCs[59], others claim that tablets are not a threat for laptops[60], instead it's the tablets that will be replaced by smartphones[61]. What adds to the confusion are the blurring lines between smartphones and tablets, and between tablets and laptops, as discussed in 2.2.2. In this review it is considered that tablets and smartphones have not (yet) replaced each other or PCs, thus these two types of devices are discussed later: smartphones in 2.2.3 as smart devices, replacing older feature phones, and tablets in 2.3.1, as in-between applications.

2.2.2 Multifunction devices

Multi-function devices (MFDs), in theory, can decrease the number of needed separate electronic apparatus and thus reduce the WEEE that is created. The term MFD refers most often to office printers used for copying, printing and scanning, but the idea of combining several functions to one device, creating a a hybrid device, has been used in consumer electronics as well[62].

As an example, (smart)phones equipped with a camera have cut the digital still camera sales tremendously during the past years[63,64]. This trend is depicted in Figure 20.

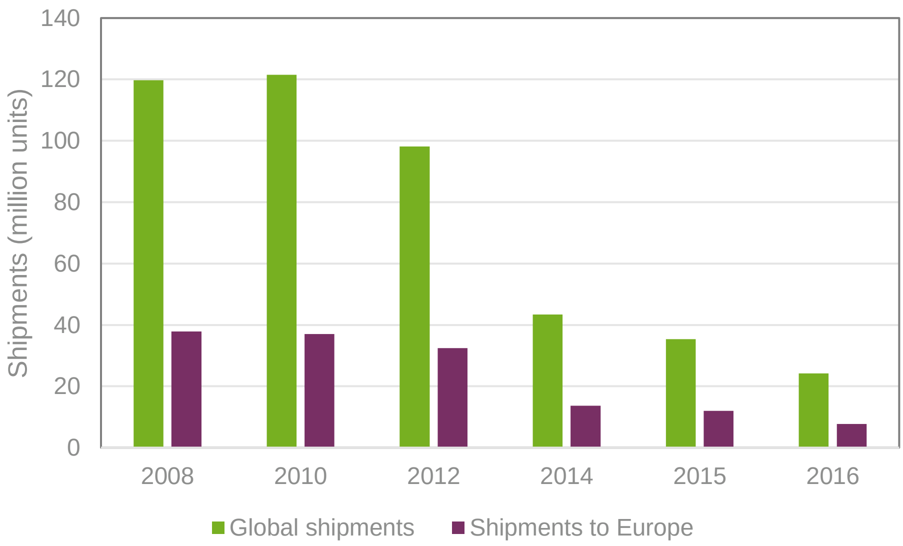

Figure 20. Digital still camera shipments worldwide and to Europe. The figures include both built-in lens cameras and interchangeable lens cameras.[65]

A more recent example of hybrid devices is the category of electronics that have been born between smartphones and tablets by the introduction of "phablets" that combine the characteristics of the two gadgets. It can be described as a mobile device with a screen size between 5 to 7 inches, although the range seems to vary according to a source.[66] Consumers' growing interest in phablets has already been analysed to have affected the sales numbers of especially smaller tablets, which have been in a downturn in the past few years[67,68]. This trend can also be seen in Figure 21.

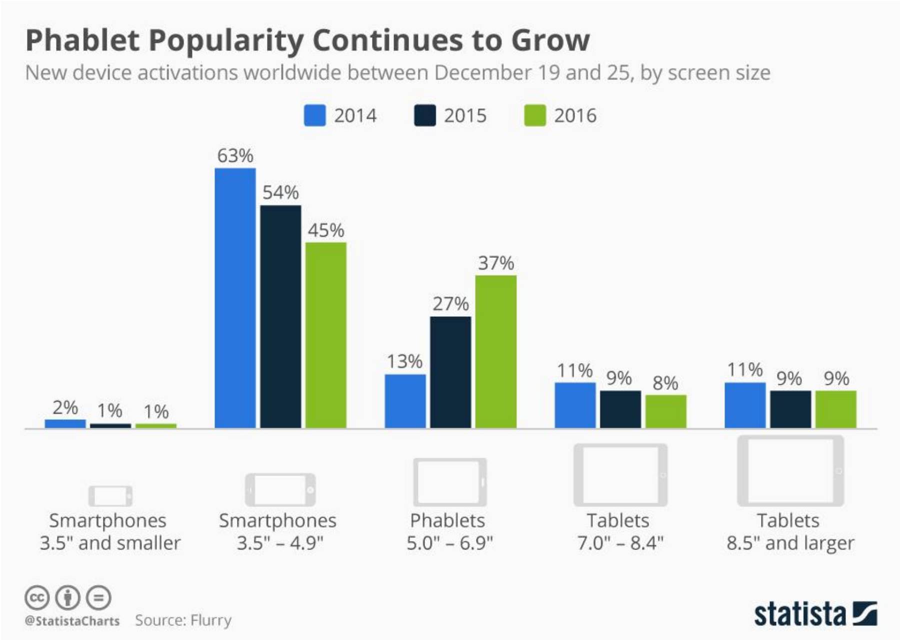

Figure 21. New device activations worldwide in the holiday season by screen size in 2014-2016.[69] *(Image courtesy of Statista)*

The consumers' preference for larger screens may raise questions regarding the critical raw materials needed for the production of the displays: Will the phablets replace both smartphones and tablets per user, or will the consumers take to even larger tablets to supplement their phablets? If the transition from smartphones to phablets does occur, recycling may require stronger pre-treatment in order to meet the requirements of metals recovery processes, which have earlier been able to feed smartphones as they are in the processes. On the other hand, if flexible displays (refer to section 2.1.2) become more common in devices, perhaps the recovery processes may deal with the larger devices.

Another example of a hybrid device is a 2-in-1 laptop that combines a laptop with a tablet: the display of the laptop is a detachable tablet. Because of the structure, the gadget is also called a detachable, whereas the "normal" tablets are called slate tablets to distinguish them from the detachable ones.[70] They are foreseen to replace especially PCs[70,71], or high-end larger slate tablets[72]. In 2015, 8.1 million detachable devices were sold worldwide[71].

The hybrid devices are also utilized as domestic appliances. An example of these apparatus is an all-in-one washer, or a washer-dryer combo, not to be confused with a separate washing machine and a dryer stacked on each other. These devices have the potential of reducing the WEEE as using a washer-dryer eliminates the need for a separate drying unit. The washer-dryer combos have been more popular in Europe and the Far East due to the commonly smaller apartments compared to the U.S.[73]

2.2.3 Smart devices

Some commonly used home appliances already have their smarter counterparts on the market. They are essential parts of the IoT. Equipment-wise, any smart appliance generally features at least a built-in network capability. For instance, a smart fridge, which was introduced already in 2000 features, in addition to a connectivity device, a touch screen panel for commands and interaction. The sales of smart fridges have remained low.[74]

Instead, a smart TV has been more popular. In the end of 2015, the share of smart TV shipments worldwide accounted for about 50 % of all the television shipments. Moreover, global smart TV shipments exceeded 100 million units in 2015, and it was estimated at that time the shipments would increase to 106 million in 2016, and by 2020 the smart TV shipments would reach already 134 million units globally.[75]

The most popular smart devices are anyhow smartphones, of which global shipments exceeded one billion units in 2013[76]. In the same year shipments in Europe reached 166 million devices[77]. Today, almost every mobile phone sold is a smartphone: for instance, nine out of ten mobile phones sold in France were smartphones in 2016[78]. What affects the large shipment and sales numbers is the rather short lifetime of smartphones, as already mentioned in 1.2: 92% of consumers think that they will own their current mobile phone less than four years before replacing or discarding it[79]. The expected length of mobile phone ownership is shown in the following figure.

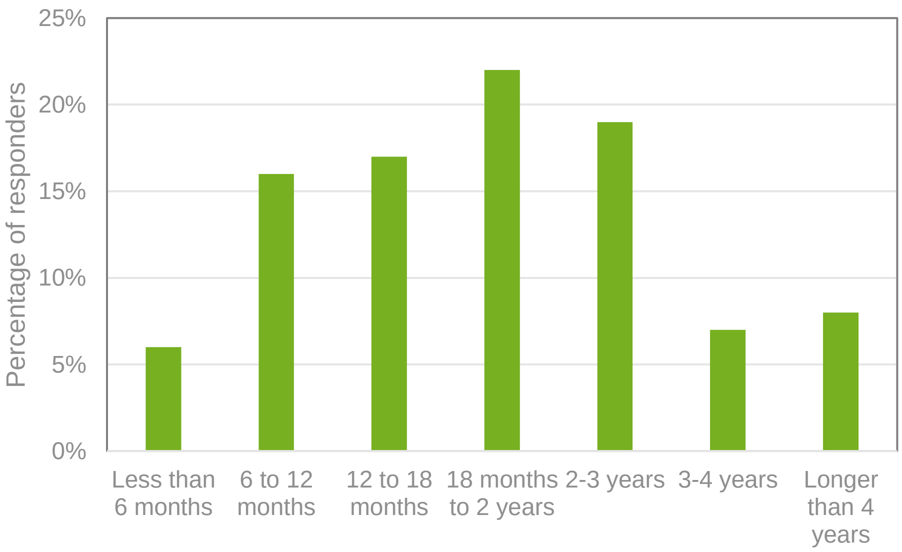

Figure 22. The time consumers think they will own their current mobile phone from the date of purchase until replacing/discarding it. The survey was conducted in 2012 in the following countries: The U.S., Brazil, China, India, Indonesia, Korea, and the U.K.[79]

The growing numbers of smart devices result in increase of especially screens and wireless network devices in WEEE. When taking into account the tremendous number of smartphones eventually ending up in WEEE, it also means an increase in magnetic materials, which are used in smartphones' data storage, vibration, microphone and speaker. In addition, if the phones with non-removable batteries become more common, also the number of batteries in WEEE will grow[80].

2.3 In-between applications

In-between applications, in this review, are considered as devices that are designed to replace the outmoded devices, but because they don't fulfil all the needs the previous gadget fulfilled, these new gadgets are more likely supplementing than replacing the previously sold appliances. The devices to be covered in this chapter are limited to two types: gadgets that exhibit an increased mobility, and robotic applications.

2.3.1 Applications with increased mobility

As discussed earlier, there are different opinions on whether the PCs are being replaced by tablets and in which proportion. There is a statistic suggesting that by 2016 about half of the tablets sold in the U.S. are replacing PCs. In the same study it was also estimated that the percentage of tablet sales considered to replace PC sales flattens out by 2020, reaching about 55 %.[81] Therefore it is not expected that the tablets will replace PCs entirely.

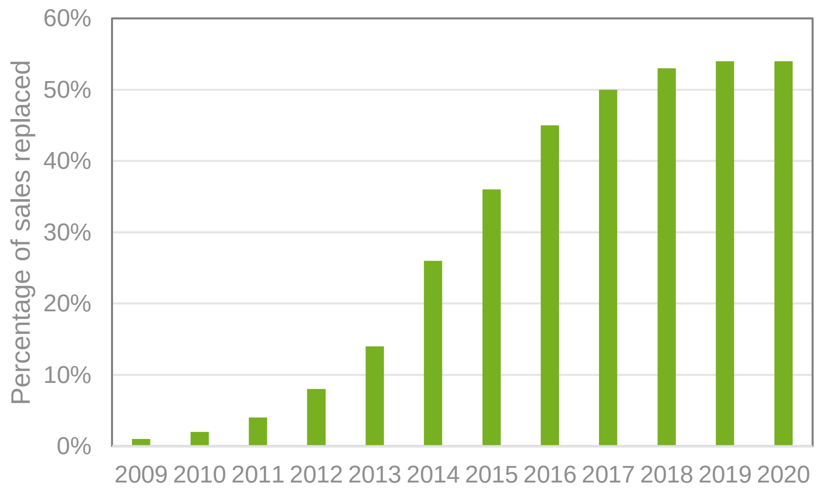

Figure 23. Percentage of tablet sales in the United States that were considered to be a replacement of what would have been PC sales is presented for time period 2009-2020. The figures from 2014 forward are forecasts.[81]

Also the growth of global shipments of tablets has stabilised in the past years, and the shipments are expected to reach about 250 million units in 2016. This is illustrated in the following figure.

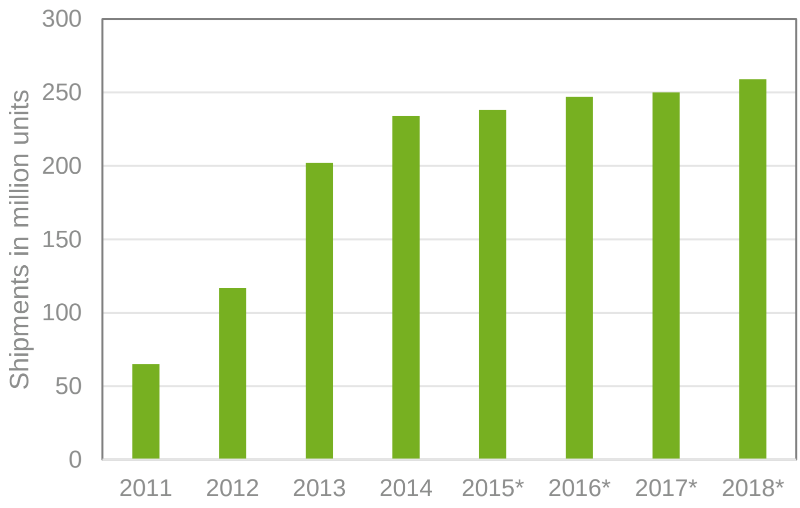

Figure 24. Realised and predicted(*) global shipments of tablets from 2011 to 2018.[82]

Other trendy mobile gadgets to be highlighted are wireless speakers, especially Bluetooth connected, which enable a wireless audio experience. Within the less demanding consumers the mobile speakers can replace the wired home audio systems, but often the small portable speakers are purchased to supplement the home audio devices, and to be used on the move. Therefore, the home audio market is on the rise, owing to the shipments of Bluetooth speakers that grew by 72 % in 2015.[83] The increased popularity of speakers means more magnets to be found in the WEEE.

2.3.2 Domestic service robots

The second subcategory is formed by domestic service robots, of which technological maturity is not yet at the level where they could actually replace the more conventional human-operated applications, but because they are autonomous to some extent, there are consumers who are still willing to purchase them. For example, robot vacuum cleaners fall under this descripction on their current technology level: in most cases they are meant to supplement a regular human-pushed vacuum cleaner instead of replacing them[84].

Nevertheless, some robots performing chores outside of the house seem to be more adapted for replacing the conventional machines. For instance, robotic pool cleaners are in some cases even more effective than other pool cleaning systems. On the other hand, they can be considered to be a continuum to the earlier systems, suction-side and pressure-side pool cleaners, which are automated as well[85].

Robotic lawn mowers have gained popularity especially in Europe where their sales numbers surge[86]. Like robotic pool cleaners, robotic lawn mowers can also replace the more conventional models in many cases without compromising the result. It seems that only their relatively high price has hindered their becoming the number one choice for the customers.[87] Robotic lawn mowers can be seen to replace above all motored lawn mowers, which is why they can be seen to add to the WEEE stream.

The global shipments of domestic service robots are estimated to grow steadily in the following years: this is illustrated in the following figure. The survey included vacuum cleaners, floor cleaners, window cleaners, lawn mowers, pool cleaners, as well as robots used for social and edutainment purposes and robotics kitchen/chefs.[88]

The increased use of domestic service robots results in more batteries, sensors and lasers to be found in WEEE.

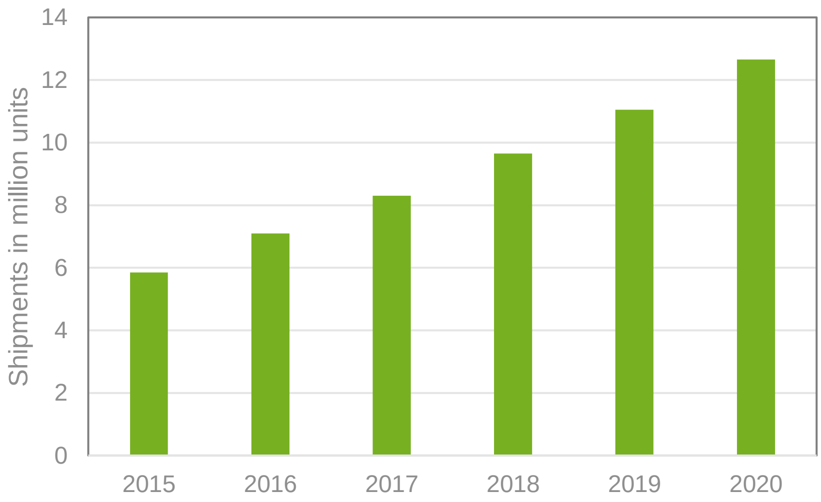

Figure 25. Domestic service robots' unit shipments worldwide from 2015 to 2020. The figures from 2016 forward are forecasts.[88]

2.4 Energy harvesting and storage

Being energy self-sufficient is one of the trends in living. Consumers are encouraged to equip their homes with photovoltaic (PV) solar panels, wind turbines, geothermal heat pumps, combined heat and power systems, and batteries for energy storage. Installing such technologies ensures benefits for consumers in many EU countries: receiving financial incentives from feed-in-tariff payments and bill savings from not having to pay for electricity from the grid. Supplying excess electricity to the grid by consumers is made possible by developing current electricity networks to so called smart grids.[89,90] Smart grids are designed to intelligently integrate the actions of all types of users connected to it - generators, consumers and those that do both - in order to efficiently supply sustainable, economic and secure electricity[91].

The amount of PV panel waste created by 2050 in countries with the most ambitious PV targets is estimated in the following figure. The numbers include the PV waste from all types of origin, not only residential. The graph takes into account two scenarios, regular-loss and early-loss. The former assumes a 30-year lifetime for solar panels, with no early attrition, whereas the latter takes account of “infant”, “mid-life” and “wear-out” failures before the 30-year lifespan.[92]

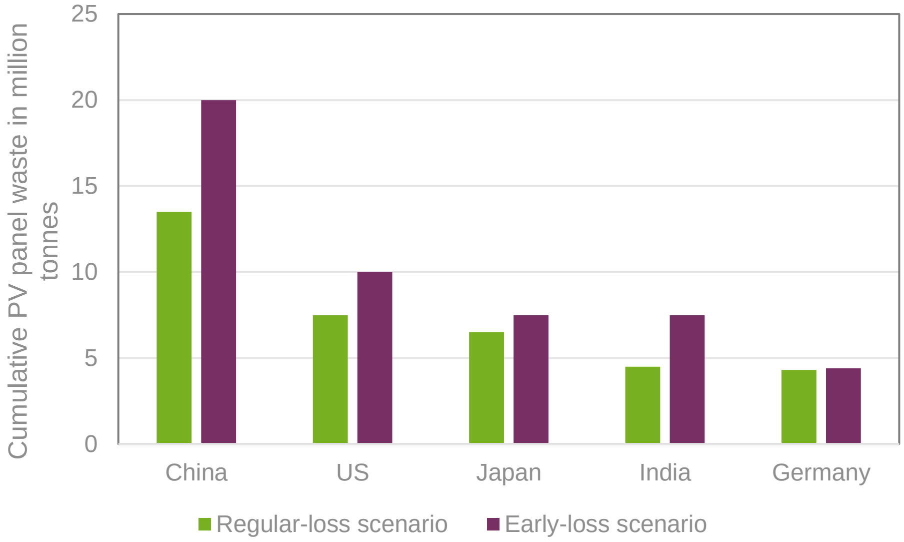

Figure 26. Estimated cumulative waste volumes in million tonnes of five countries for end-of-life PV panels in 2050.[92]

Batteries are widely used in consumer electronics due to the desire for mobility. Li-ion and NiMH batteries currently share more than 80% of the rechargeable batteries market[93]. Li-ion batteries are dominating in the portable and mobile devices market (e.g. laptop, cell phone) since around 2000[94], while NiMH shares a large proportion of portable electronics such as camcorders, as well as hybrid and electric vehicles[93].

New types of Li-ion based batteries are continuously introduced to the market. $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$, $LiFePO_4$, $LiMnO_4$, $LiMnO_4/LiTiO_{12}$, and Li-polymer batteries are some of the secondary batteries available on the market.[93]

In addition to batteries, consumer electronics can receive power through a PV cell. Solar-powered chargers, cell phones, wearables, speakers, to name a few, are examples of solar mobile devices available for consumers today.[95] One potential sector of solar-powered consumer electronics involves transparent PV, which enables any surface to be used for solar energy harvesting. The desire is to develop materials in the form of thin films that can be used to coat any surface. The coming innovations will have a high impact on consumer products like televisions, camcorders, smartphones, and other portable electronic devices. [27]

3 Trends in electronics manufacturing

The chances occurring in electronic manufacturing industry and how they affect the composition and design of future electronic devices, and further the WEEE, are discussed in this chapter.

3.1 Miniaturisation

The demand for miniaturisation is coming from both the need for smaller assemblies in specific applications, and the need to reduce material costs via smaller components that function as well as physically larger ones.[96] Especially the cost savings has been the biggest motivation for the miniaturisation of electronics, which in turn has made it possible for computer technology to penetrate the consumer market in the extent it is today.[97]

The functional density, or the number of functions a product has per volume, has increased exponentially with smaller components. Miniaturisation has therefore been the key development step before being able to design multi-functional devices for the consumer section - a mobile phone with a digital camera and sound reproduction as an example.[98]

Miniaturisation has therefore induced the affordability and improved functions of consumer electronics today, resulting in the widespread use of various consumer devices and, consequently, the increase in WEEE. Miniaturisation leads to an increased number of smaller components with smaller concentrations of valuables per application which may complicate recycling.

However, the development of miniaturisation in electronics has not yet come of age. Novel miniaturising techniques exploit so called 2D electronics, which is based on two-dimensional, atom-thick allotropes of carbon, silicon, phosphorus and tin. Molecular electronics, on the other hand, is considered as the ultimate goal of electrical circuits miniaturisation. This branch of nanotechnology uses single molecules or collections of them as electronic building blocks.[99]

3.2 Printed manufacturing

Printed electronics refers to electronic components manufactured by printing methods on substrates such as paper, plastic or textile. The manufacturing method is very cost-effective, and offers both high-volume and high-throughput production of electronic components or devices that are light, thin, flexible, and inexpensive. Figure 27 shows facilities for making printed electronics.

Nevertheless, printed electronics is not seen as a substitute for conventional silicon-based electronics in the fields where high performance is required. Instead, the technique is considered suitable for producing materials aiming at low-cost and high-volume market segments. The possible, and partly realised applications include for instance RFID tags, photovoltaic cells, sensors and OLED displays.[100] The printed items can also be electronic components, such as conductors, coils or circuit boards, and often the printed components are combined with conventional electronic components in the end product.

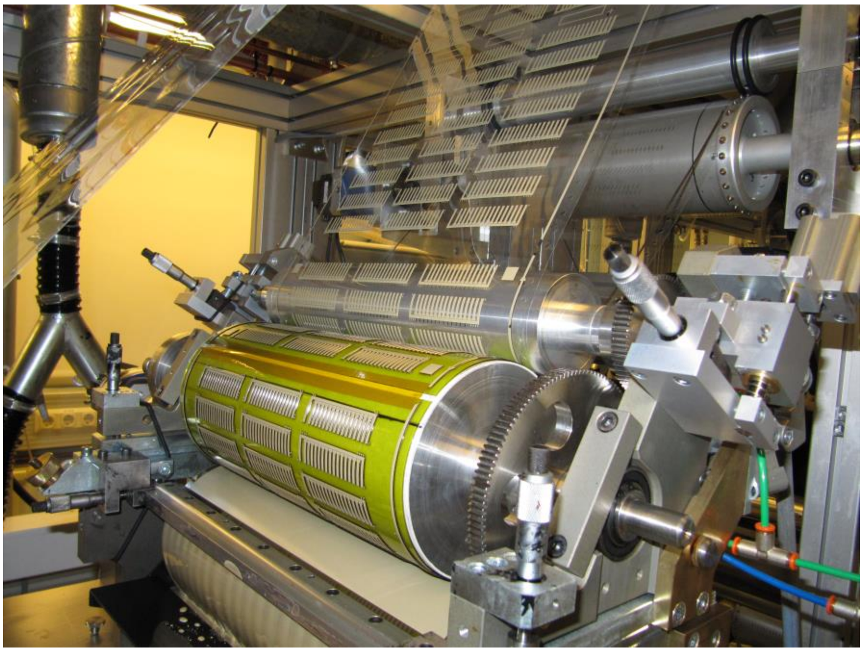

Figure 27. Memory circuits being printed at VTT pilot printing facilities. (Image courtesy of VTT)

From the recycling perspective, the recovery of valuable materials from printed electronics may require novel techniques as the materials, usually metals, may be located on wide areas but in very thin layers. If the printed electronics is combined with conventional electronic components in a device, it is likely that the amount of printed metals is insignificant compared to the valuable materials in the conventional components.

Improving the recyclability of printed electronics is however under investigation, realized by techniques such as the fabrication of sustainable multi-layer assemblies. A series of special polymer layers and binders are being developed to allow straightforward unzipping performed at the end-of-life, permitting easy reuse and recycling of structures. It is anticipated that the recovery levels in typical assemblies will be improved significantly [101].

The emerging field of organic electronics is strongly related to printed manufacturing, as printing is one possible way to manufacture organic electronics. By printing organic inks, it is possible to make electronic devices that are flexible, stretchable and soft - features that cannot be achieved with silicon or any other inorganic materials. This is why their potential future applications are enormous.[102]

In addition to a vast selection of potential applications enabled by organic electronics, there is also a potential for greater sustainability. This results from using materials that are synthesized rather than mined from the earth, and from the features of the end product: the device that is potentially biodegradable.[102] Biodegradable consumer electronics would cause a groundbreaking change to the disposal of electronics. This vision is however rather futuristic in our time.

3.3 3D printing

In 3D printing, the product is fabricated by depositing material, or ink, in successive, thin layers on top of each other. The layers are defined as digital cross-sections by a software. The cross-sections can be constructed in a number of ways depending on the type of the 3D printer. In each case, after the layer is complete the built surface is moved as much as the layer description requires, and the next layer of material is printed on top of it.[103] The first 3D electronics printer was introduced in 2015. It was able to print both plastic and conductive material, which made it possible to print the circuitry and the physical structure of the product simultaneously.[104]

3D printing was first used to make limited-functionality models and prototypes. More recently, however, the technology has been exploited more in final-product based manufacturing in various fields. A growing interest is seen in using 3D printing as an individualised or personalised approach to manufacturing, such as for customized circuitry and sensors, and in the longer term for wide-area electronics. Furthermore, this manufacturing method is providing an inexpensive, low-volume and low-risk route to market for entrepreneurs with novel products.[103,105]

The use of 3D printing may diversify the composition of WEEE, as it becomes more economical to produce smaller batches of a certain product. Moreover, there may be less separate printed circuit boards, provided that the interconnects can be printed inside the housing of the product[106], which may complicate the separation process in the WEEE recycling.

3.4 Integration

By integrating electronics into protective structures, conventionally dummy plastic parts can be made interactive. Different techniques, like thermoforming and injection moulding, are being investigated. Combining the freedom of shape and flexibility of printed manufacturing or 3D printing techniques, and the technologies from flexible electronics a new manufacturing method is being developed.[107]

A method for integrating printed electronics and chip-based components into injection moulded plastics has been issued recently. The printed electronics include circuitry, touch controls and antennas, whereas the discrete electronic components can be for example LEDs. The technique is referred to as injection-moulded structural electronics (IMSE). The electronics based on IMSE, which are often illuminated indicators and control panels, as shown in Figure 28, are foreseen to be employed in home appliances, wearables and health care.[108]

Figure 28. A control panel based on IMSE technology. (Image courtesy of TactoTek Inc.)

The technique is seen to enable cost-effective mass production.[108] However, from the recycling perspective it means that structurally integrated materials in general make it difficult for recovery of valuable materials, and also for disassembly as embedded systems increase the durability of components in the size-reduction step of WEEE recycling[109]. On the other hand, the amount of plastic used in the final assembly will be reduced, and the useful life of the device may be longer due to the more durable structure.[110]

4 Facilitations for future WEEE processing

In this section, the possible electronic technologies and manufacturing solutions, which may be utilized in recycling industry or may benefit the treatment of the WEEE, are presented. Beside RFID and active fasteners in the product design discussed in this chapter, sensor technology and robotics are in a focus. The latter will be presented in section 5.

4.1 Radio-frequency identification (RFID)

The first steps in utilization of product tags in environmental management has been taken over a decade ago[111,112,113]. However, commercial and concrete applications and utilization within recycling industry is still lacking. The most promising technology in identification has been the radio-frequency identification (RFID) technology, which was described also in section 2.1.5 regarding to systems for new needs.

Possible utilization of RFID tags in recycling industry can have multiple functions depending on which stage of the recycling chain it would be applied, since different type of data are required in different stages of the treatment chain. Table 6 summarises the RFID's benefits for the recycling industry.

Table 6. A summary of benefits that RFDI technology could provide for different stages of recycling chain. (Derived form [42])

Recycling stage	Benefit
Discarding EEE	RFID tag may provide information to consumer: • Whether the equipment should be disposed or sold for reuse • To which recycling operator the equipment should be disposed (information on operators specialised on target equipment)
Collection	RFID tag may provide information about whether WEEE ends up in other waste streams such as in MSW.
Dismantling	RFID tag may provide information to recycling operator: • Construction plans of the device could be assessed in order to enable best-practice dismantling operations (possible information also on maintenance) • Estimate the value of the device or the precious materials contained within it. • Obtain information about how to dismantle the device and about potential hazardous substances contained within it.
Sorting	RFID tag may provide information to recycling operator: • Estimate the value of the device or the precious materials contained within it. • Obtain information about potential hazardous substances contained within it.

Few visionary concepts of combining RFID information with semi- or fully automated dismantling lines to categorize incoming equipment as well as separate components have been presented in the literature[42].

However, some requirements and barriers for efficient utilization of RFID technology in recycling industry still exist. These are listed below [42]: (katsu sivu 171 Schindler 2012 raportista)

Requirements:

- A unique product identifier (e.g. electronic product code)
- Radio frequency tags and readers to ensure timely and automatic identification of product.
- Filtering, collection and reporting mechanisms for managing tag reads.
- An interface to a distributed product information database (e.g. the Electronic Product Code (EPC) Information Service) linked to an information look-up service (the Object Name Service) to ensure completeness and accuracy of product information.
- Standardised vocabularies for communication across the supply chain.

Barriers:

- To benefit from RFID in the disposal phase, every product needs at least one tag. This is problematic especially regarding the market penetration of long-life products even when product tagging would be mandatory from now on for each product.
- Unlike conventional manufacturing and assembly processes, disassembly operations are characterised by a high variety in the type, quality, and condition of returned products and because of the numerous options available, this leads to high levels of uncertainties in determining the destiny of a product at the end of its life. As a result of the uncertainties associated with returned products, effective recovery of value requires extensive information about the product identity and its condition at the time of return.
- Additional barriers that have been highlighted through expert consultations within the research by Schindler et al.[42]:
    - Commercial barriers: investment in automation; increased reuse could decrease number of sales.
    - Legal barrier: current legislation does not set the right incentives.
    - Organisational barriers: new knowledge profiles and working methods are needed; there is a need for specialisation.
    - Social barrier: stakeholders might not be willing to invest.
    - Technological barrier: high costs of infrastructure for collectors and recyclers; automated dismantling might be very complex.
    - Commercial requirements: expenses for RFID infrastructure must be acceptable for ELV handlers/recyclers; expenses for RFID infrastructure must be acceptable for OEMs; expenses for information handling and maintenance have to be considered.

As a conclusion, RFID based recycling may improve the efficiency of WEEE recycling in the future. However, this requires a sort of paradigm shift in the data and information ownership and utilization throughout the whole value chain. Manufacturers need to open data for others and trust between stakeholders must be created.

4.2 Design for disassembly

Product design has been recently highlighted as one key measure when shifting towards circular economy. Product design has a significant effect on the recycling, since decisions and selection of connection methods and number of connections between components and parts, as well as materials choices are carried out in this stage. Since all different types of connection methods perform differently in recycling systems, improvements in the recycling efficiency can be made already by taking this into consideration. However, the selections should be carried out without losing the functionality of the object as well as taking into account aspects such as design.

In the recent years, active dismantling or disassembly has gained attention in the academia[114,115,116,117,118,119]. Active dismantling or disassembly is a concept which enables separation of parts/components from products for recycling through the use of smart materials or structures in the product design. The detachment/loosening function is activated through a single or combination of external triggers. As an example, if products are designed with shape memory snap fits, disassembly is initiated when product is heated. Upon heating, all snap fits are deformed, thus releasing the individual components and consequently the products are dismantled.[114] Beside thermal triggers, a number of other type of triggers have been identified as presented in Table 7.

Table 7. Overview of triggering methods and their possible effect. [119]

External trigger mechanism	Possible trigger principle	Possible effect
Mechanical force	• Centrifugal force • Acceleration • Water jet	**Deformation** • Elastic • Plastic **Material failure** • Erosion • Splintering • Breakage **Function failure** • Removal of blockage elements
Vibration	• Mechanical vibration • Sound waves • Water waves	**Material failure** • Destruction after reaching natural frequencies **Function failure** • Loosening of tight fits
Pressure	• Pressure variation (air / water)	**Deformation** • Elastic deformation • Plastic deformation **Phase transition** • Melting • Evaporation • Sublimation
Electrical	• Electric current	**Deformation** • Elastic deformation • Shrinking • Expansion **Phase transition** • Melting
Chemical reaction	• Reagent in surrounding atmosphere (pH-level, hydrogen, H_2O, …) • Submerging in reagent	**Deformation** • Shrinking • Expansion **Material failure** *Changing material properties* • Corrosion • Dissolving • Pyrolysis

		• Pulverisation
Thermal reaction	• Joule effect • Radiation (Laser, infrared rays, …) • Microwaves • Submerging in hot water tubs	**Deformation** • Elastic deformation • Plastic deformation • Shrinking • Expansion **Phase transition** • Melting • Evaporation • Sublimation **Material failure** *Changing material properties* • Creep • Brittleness • Viscosity change *Material breakage* • Thermal shock effect • Diverse material expansion coefficient • Inverse material expansion
Magnetic field	• Presence of electromagnet (Magnetising vs. Demagnetising) • Magnetic Ray Interference (MRI)	**Deformation** • Elastic deformation • Plastic deformation **Phase transition** • Solid to liquid **Function failure** • Attraction vs. Repulsion
Light radiation	• UV-radiation	**Material failure** • Surface corrosion • Pulverisation due to material property changes • Brittleness
Biological action	• Presence of bacteria • Enzymes inducing chemical reactions • Bionically designed systems	**Material failure** *Changing material properties* • Corrosion • Dissolving • Pulverisation *Changing material phase due to eating bacteria* • Melting • Evaporation • Sublimation

Beside access authorization (who can detach the connection; all vs. manufacturer or authorized operator) and structural selections (box, frame, sectional and cover), also the product's functionality need to be guaranteed. This depends strongly on the trigger selection, since it initiates the disassembly process. The connector developer or manufacturer has to make sure that the trigger will never be accidentally reached during its operational period.

Undesirable disassembly would affect the product's functionality and could cause hazardous situations. Solutions such as significantly increased triggering level that cannot be reached during the product's active life, or combination of triggers that need to be present simultaneously to activate disassembly, have been developed.[114]

Currently, the research is focusing on the effect (environmental, economical) of active fasteners on dismantling of specific WEEE products, and further on the entire recycling chain efficiency. A recent study by Peeters et al. revealed that the preferred EoL treatments, as well as the economic and environmental benefits of implementing design for active disassembly, are strongly product dependent. Based on the analysis, the application of pressure and temperature sensitive fasteners is expected to be economically viable for products that are placed on the market in a product-service system (PSS), and which will be separately collected with a high collection rate for the purpose of repair, refurbishing, remanufacturing, cannibalization or recycling. As an example of these type of products are medical monitors and credit card payment terminals. The implementation of impulse sensitive fasteners is considered to be suited for products sold in a traditional sales-oriented business and used in a PSS. In addition, the implementation of these fasteners is demonstrated to result in a substantial reduction in environmental impact in several product categories. However, original equipment manufacturers (OEMs), which sell their products in a traditional sales-oriented business model, may not often benefit from the implementation of these fasteners, due to the fixed contribution fee per product, which is charged by the joint collection schemes. [118]

5 Current and future mechanical treatment technologies

Current mechanical treatment of WEEE relies mostly on technologies such as crushing, sieving and separation based on magnetic, eddy current, density and sensor techniques. In this chapter the emphasis has been put on technologies that have had great development during the last decade and may enter the commercial stage in the near future. However, an exception has been made with the sensor separation technology, which is already at the commercial stage, but is seen as an important technology field to be presented.

5.1 Automatic and active disassembly

During the recent decade, robotic and automated disassembly of end-of-life products has gained significant attention [120,121,122,123,124,125,126] since more parts, components and materials are desired to be dismantled undamaged. In addition, reducing labour costs by replacing manual dismantling with automated dismantling has been one of the key aims. Parts and components can be either reused or fed for further material recycling. Hoverer, the control of component and part quality needs to be sufficient in order to detect whether they are suitable for reuse. Therefore, at the moment the emphasis in robotic and automated dismantling is on dismantling the parts and components for material recycling.

Various technical approaches in the automated disassembly have been carried out. However, some main stages are relevant to all approaches. These are:

- identification (e.g. sensors),
- processing data from identification, and
- disassembly operation based on processed data.

In recent years the development and research in disassembly has focused more on cognitive robotics, since the uncertainties and variations in end-of-life products create problems to common disassembly. In Figure 29, an approach for the system architecture in the cognitive robotic dismantling (CRD) is presented.

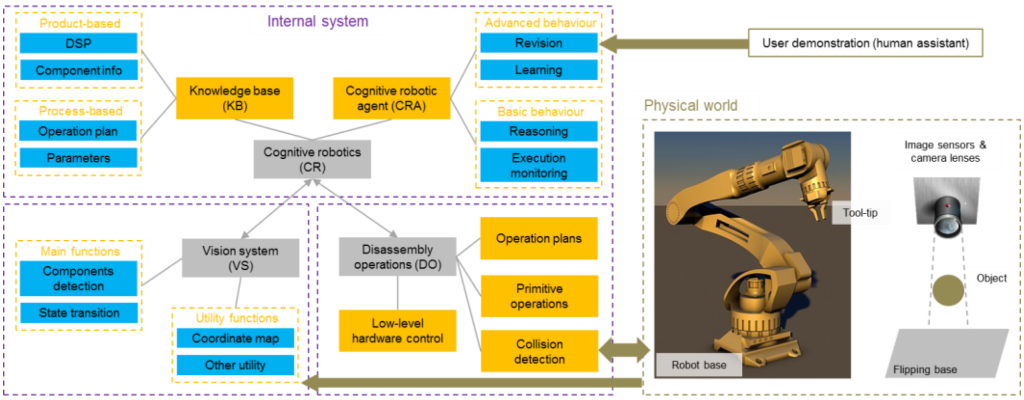

Figure 29. A schematic approach of system architecture in robotic dismantling (derived from [122])

In the CRD human behaviours are emulated to adapt better for the variations and uncertainties. In a summary, the CRD system will keep trying a number of possible ways to remove each main component in each state of the disassembly. A user will assist the system if it fails too many times. Finally, the cognitive robotics program will be modified so that the successful process will be learned and re-used when the same model is seen again. The CRD system (Figure 29) consists of three independent modules: the cognitive robotics module (CR); the vision system module (VS); and the disassembly operation module (DO). The cognitive robot agent (CRA) controls the behaviour of the CRD system in relation to the to the perception of the environment and existing knowledge. The behaviour is influenced by four cognitive functions: reasoning, execution monitoring, learning and program revision.[122]

The CRD research by Vonbunyong et al. focused on the disassembly of LCD screens. For the methodology development and analysis, statistical information was obtained from examining 37 different LCD screens. Main components to be dismantled from each other were: back cover, PCB cover, PCBs, carrier, LCD module and front cover.[122,127,128] In Table 8, the disassembly outcome of an LCD screen is presented.

Table 8. Outcome of the disassembly process. (derived from [127])

Component	Weight of the component [g]		Detached part of the main component [%]	
	Ideal case (no damage)	Actual result (damage)	Main part	Residue
Back cover	343.3	320.0	93.21	-6.79
PCB cover	163.5	77.7	47.52	-52.48
PCB-1	30.1	26.9	89.37	-10.63
PCB-2	160.5	143.0	89.10	-10.90
PCB-3	68.6	47.7	69.53	-30.47
Carrier	691.7	631.1	91.24	-8.76
Front cover	159.4	172.6	108.28	+8.28
LCD module	1000.7	1043.9	104.32	+4.32
Whole product	2617.8	2462.9	94.08	

5.2 Size reduction

Size reduction is carried out on the feed material to decrease the particle size to be suitable for separation processes, as well as to liberate different materials and components from each other. Liberation of materials/parts is vital for efficient separation, otherwise desired materials end in wrong fractions and can be lost. Conventionally and currently size reduction is carried out by different type of crushers. Common crusher types are: hammer-, impact-, ring- and knife crushers. Different crushers with different breaking mechanisms are utilized for different feeds, e.g. the knife crusher is more suitable for a plastic rich feed than for a metal or mineral rich feed.

Traditional crushers operate mostly in a blind way, in which time selectivity parameters and effects are rough. Usually a rotor speed and an output sieve size are the main operation parameters. This leads partly to the generation of dust, where valuable metals have been reported to end up[9,7,3,129].

As an alternative size reduction method, which has been developed in recent decades, is electrodynamic fragmentation (EDF). The main application of this method was initially to disintegrate rocks in the mining industry in order to extract crystals and precious stones without aggressive and polluting chemical procedures, by applying electrical discharge through the specimen. The material is placed in water between two electrodes and high voltages between 50 and 200 kV are applied (Figure 30). The voltage must be higher than the actual breakdown voltage of the material to be fragmented, but lower than the surrounding medium (usually water). This is achieved by reducing the pulse rise time below 5 µs for solid material in water using a Marx generator, as described in Figure 31. The electrical discharge brings a high energy (10 to 100 J/cm) creating a plasma channel in the solid. This strong energy induces temperatures and pressures up to 10.000 °C and 104 MPa, which create pressure waves exceeding the strength of most materials and leading to the cracking of the weakest materials surrounding the plasma channel. The best fragmentation results are obtained with brittle and heterogeneous materials.

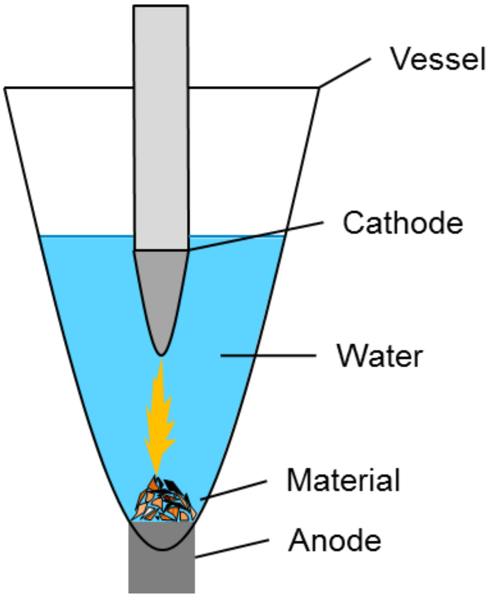

Figure 30. Principle of electrodynamic fragmentation.

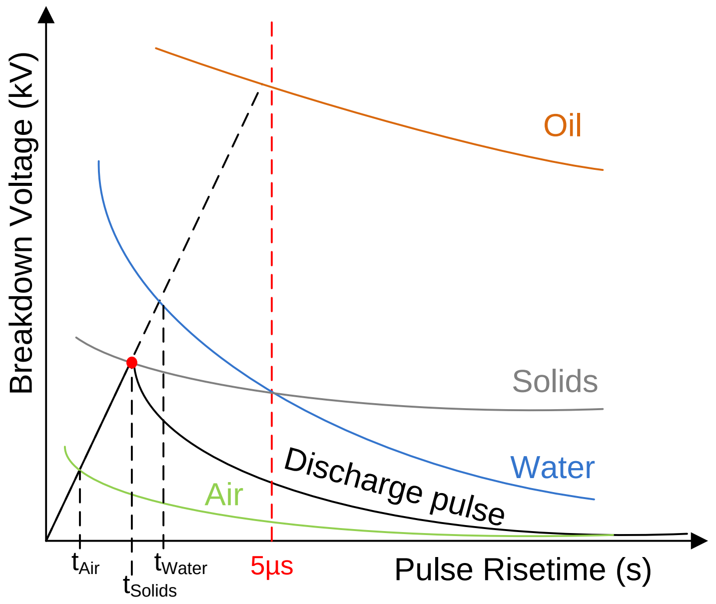

Figure 31. Breakdown voltage as a function of the pulse rising time. Solids have breakdown voltages lower than water below rising time of 5 µs. (Derived from [130].)

EDF has been applied on WEEE and especially on printed circuit boards (PCB) to liberate copper foil from glass fibre and epoxy resin[131–133]. In addition, the detachment of surface mounted components from PCBs has been investigated recently. The studies have shown that with increased energy inputs to the system, the following effects can be expected on PCBs (see Figure 32): [132]

- depopulation (detachment of components),
- delamination, and

- board destruction.

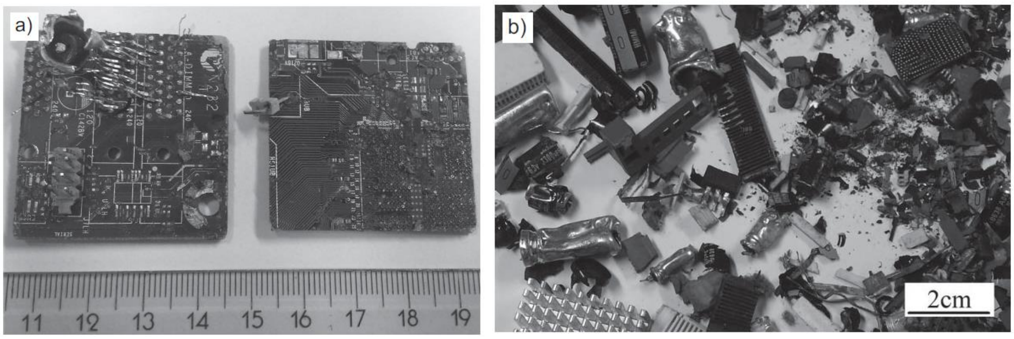

Figure 32. a) Depopulated PCBs, and b) detached surface mounted components after the EDF treatment. [132]

During the initial EDF processing of numerous Printed wiring boards (PWB) samples it has been observed, that when applying increasing energy levels, the components mounted on the PWB are removed first. Then, the PWBs are delaminated, and finally the processing continues towards entire physical fragmentation of the board fragments into polymer powder, metal foils, and glass fibers.[132]

Commercialization of EDF has taken its first steps around the millennium by SelFRAG (http://www.selfrag.com/recycling-examples.php). The equipment is suitable for both mining and recycling industry including WEEE treatment. After treatment, different liberated materials can be separated by means of traditional mechanical processing such as eddy current and density separation. The capacity of the equipment is around 10 t/h (http://www.selfrag.com/10ton-products.php).

5.3 Separation and sorting

After size reduction and possible size control, materials and components are separated from each other by means of mechanical separation equipment (i.e. magnetic-, eddy current-, density and sensor based separation) to produce different metal concentrates for further refining, and organic fractions for utilization or disposal. Recent development in separation technology has focused on sensor separation as well as on magnetic assisted density separation.

5.3.1 Magnetic density separation

Magnetic density separation (MDS) has been recently introduced to the industry by Liquisort (http://www.liquisort.com/eng/index.html) to accurately separate shredded plastics or shredded metals. The principle of the separator is based on the behaviour of magnetic liquid in a strong magnetic field. The liquid, which has almost the density of water outside the magnetic field, effectively increases or lowers the liquid density depending on the placement of the magnet. The advantage of the method is to achieve a controlled density gradient through the liquid bed[134]. This enhances the separation efficiency of the density separator enabling separation of materials which have nearly the same density. These are illustrated in Figure 33.

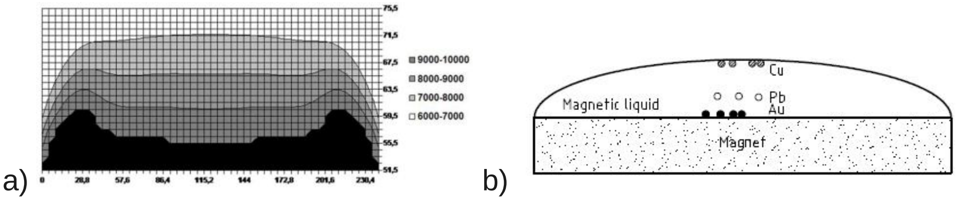

Figure 33. a) Density gradient of the magnetized liquid; and b) separation principle of MDS for gold (density 19300 kg/m^3), lead (11340 kg/m^3) and copper (8900 kg/m^3). [135]

The material is fed on a tilted conveyor, inside of which a magnet generates a density gradient in the liquid above the conveyor belt (Figure 34). When the conveyor is rotating upwards, the blades peel and carry heavy material apart from light material, which move together with the liquid to the bottom container. The bottom container can contain a sieve which separates particles from liquid that can be recirculated back to the process.

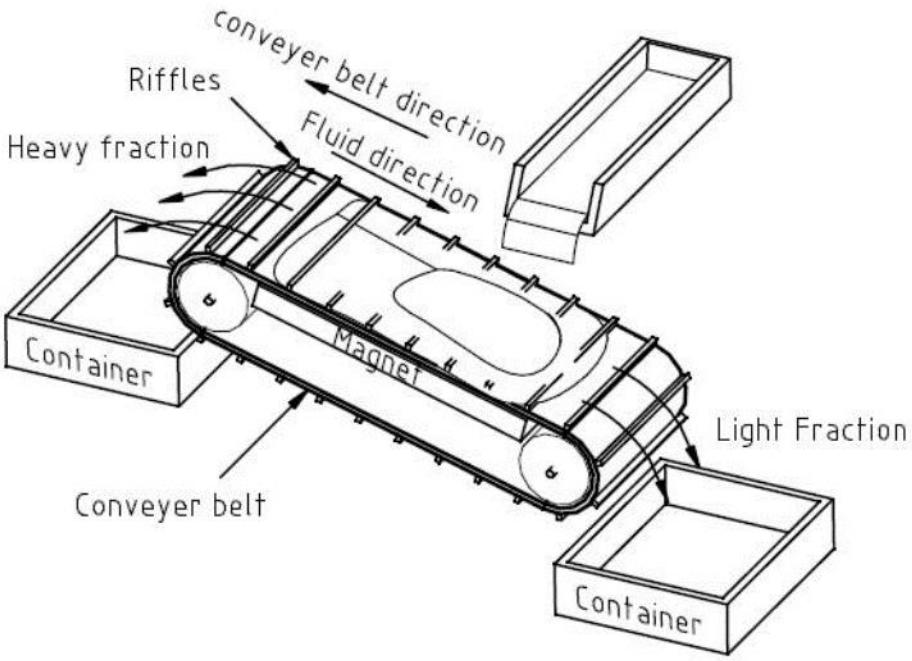

Figure 34. Principle of the MDS separator. [136]

5.3.2 Sensor separation

Sensor based indirect sorting has evolved significantly during recent decades, enabling separation of materials that have rather similar physical properties, which traditional direct separation methods have challenges to separate. Indirect sorting employs sensors to detect the presence and often the location of recyclables in the waste so that automated machines or robots can be employed to sort the detected recyclable materials. Below are listed indirect sorting methods, and in Table 9 their applicability to separate different materials.

- Eddy current based sorting
- Laser Induced Breakdown Spectroscopy (LIBS)
- X-ray based sorting
- Optical based sorting
- Spectral imaging based sorting

Table 9. Applicability of different indirect sorting methods. (derived from [137])

Material	Eddy current	LIBS	X-ray	Optical	Spectral
Non-ferrous metal	x	x	x	x	x
Plastic		x	x		x
Paper				x	
Glass				x	x
Wood		x	x		

In the following sections each method is shortly described, after which an example of applying these methods on PCB sorting is presented.

Eddy current based sorting

Differing from traditional eddy current separation, eddy current based sorting utilizes electromagnet sensor for detecting nonferrous metal fractions, based upon electrical conductivity of the sample. When a magnetic flux generated by an electromagnetic coil is passed through a conductive material then an eddy current is induced. As the materials are passed on a conveyor belt underneath the transmitter coil, an eddy current flows into the material. According to the Lenz's law, the generated eddy current opposes the secondary magnetic flux. By measuring the secondary flux, the presence of ferrous metals in bulk waste is detected. Finally, the detected non-ferrous particles are segregated by means of compressed air jet. The properties of materials affecting the process are among others electrical conductivity and magnetic permeability.[137] In Figure 35, a description of the eddy current based sorting is presented.

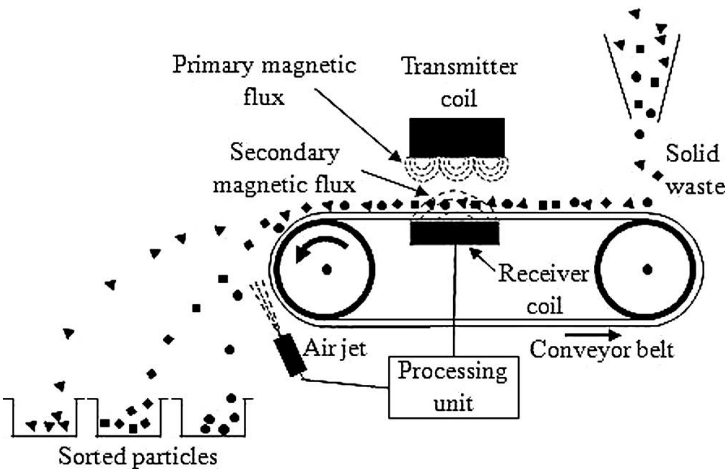

Figure 35. Eddy current based sorting technique[137].

Laser induced breakdown spectroscopy (LIBS)

Laser induced breakdown spectroscopy utilizes a high power laser pulse, which provides high dimensional spectrometric information for the analysis of metal alloys, plastics and treated wood waste. A LIBS system is composed of a neodymium-doped yttrium aluminium garnet (Nd:YAG) laser, a charge-coupled device (CCD) as a spectral range spectrometer, and a processing unit for fast data analysis. First, the bulk waste is moved into the inspection area, where the laser beam is focused over it. This leads to ablation of waste material, which generates plasma plumes. The radiation emitted from the ablated part is captured by the CCD spectrometer. The optical spectroscopy reads and distinguishes the characteristic atomic emission lines of the bulk waste followed by the detection of constituent materials. Finally, the mechanical system such as air jets sorts the detected constituent materials into their respective bins.[137] In Figure 36, a schematic figure of LIBS technique is presented.

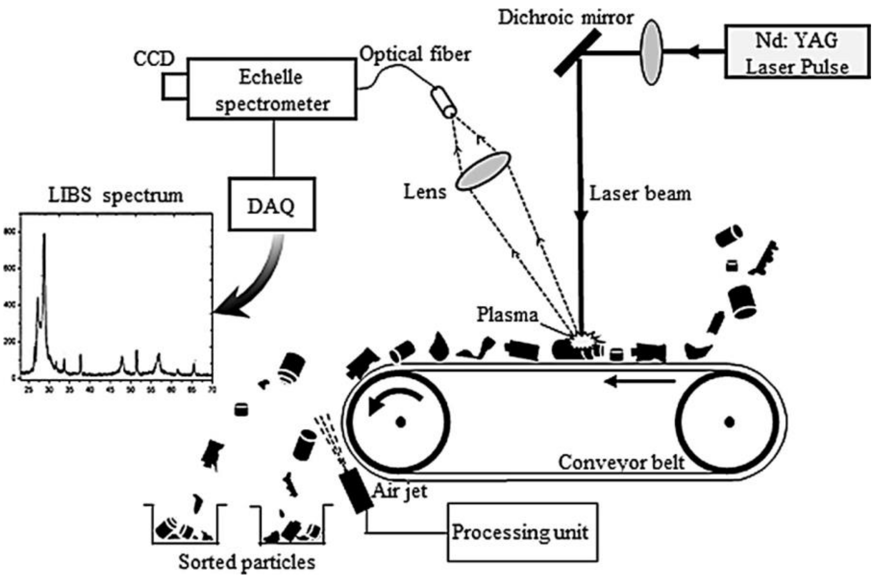

Figure 36. LIBS based sorting technique[137].

Some limitations have been reported to still exist within LIBS techniques. These are[137] :

- Significant fluctuation in signal intensity is possible, which can cause an uneven energy distribution between material composition and laser pulse due to varied plasma generation
- The excitation of pulse is limited to small region for elemental analysis
- Sensitive to surface contamination

X-ray based sorting

X-ray transmission based sorting is relatively fast, as the X-ray images are captured within a few milliseconds. The technology utilizes a high-intensity X-ray beam. When X-rays penetrate into the waste material, some of its energy gets absorbed by the material, while the rest is transmitted through to a detector. The detected radiation is analysed to provide information about the atomic density of the material. X-ray sorting can be divided into two categories: Dual Energy X-ray Transmission (DE-XRT) and X-ray Fluorescence (XRF). The schematic presentations of these techniques are shown in Figure 37.

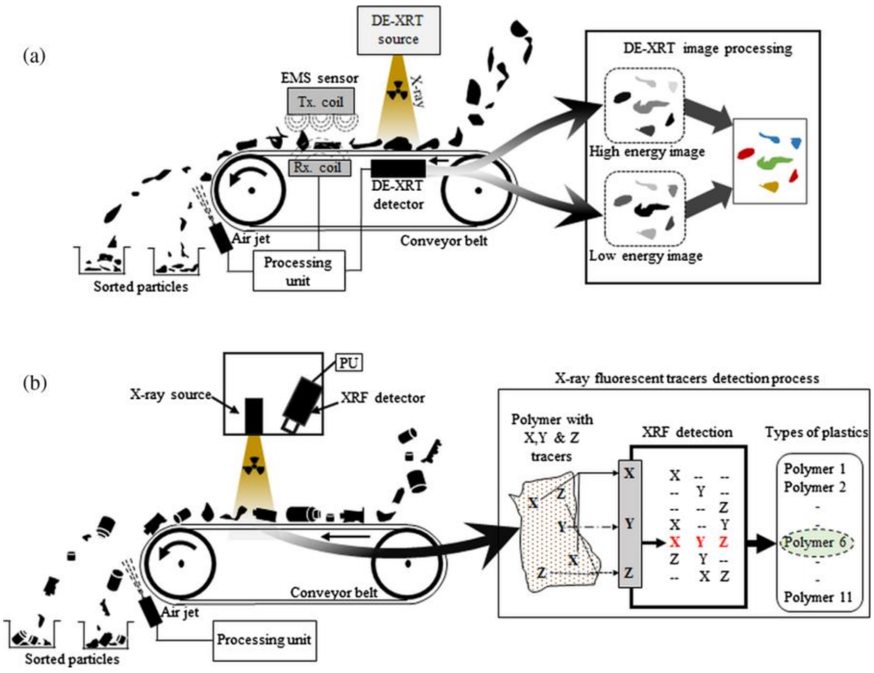

Figure 37. Schematic figure of a) DE-XRT and b) XRF separators. [137]

Reported limitations are[137]:

- Categorization between wrought and cast aluminium,
- DE-XRT's low efficiency with small particles, and
- XRF cannot differentiate between different plastics (except PVC).

Optical based sorting

Optical based sorting systems identify and detect visual and tactile type of cues such as colour, shape, texture and size which are used for separating different materials from each other. For example, a hybrid system of a colour vision and an inductive sensor array can be utilized for identifying metals such as copper, brass, zinc, aluminium, and stainless steel. In an image of mixed metals, regions with a larger red component indicate copper and brass, while regions of blue indicate stainless steel and aluminium. The final identification of material is based upon both colour differences and electrical conductivity.[137] In Figure 38, a schematic description of optical sorting system is presented.

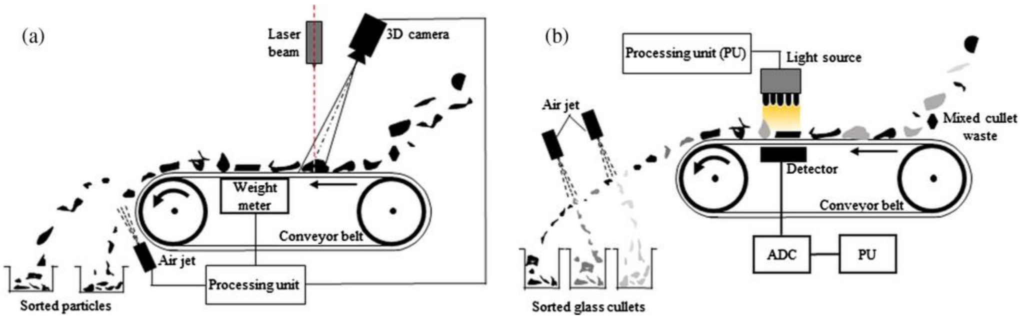

Figure 38. Optical sorting technique consisting of a) a 3D imaging camera, weight meter, belt conveyor and an air compressor and b) colour sorting technique of ceramic glass contaminants composed of a light source and sensor[137].

Some reported limitations to the optical method are:[137]

- Inductive sensors are sensitive to distance changes, and
- Complex shapes of material can cause variation in the measurement.

Spectral imaging based sorting

Spectral imaging combines both spectral reflectance measurement and image processing technologies. Spectral imaging composes of various techniques: NIR (near infrared), VIS (visual image spectroscopy) and HSI (hyperspectral imaging). In NIR and VIS technologies either infrared wavelengths or reflected light is detected, on which a spectrum is created and further on the separation is carried out. In an HSI technology images are produced over a continuous range of narrow spectral bands, after which the spectroscopic data is analysed and utilized for separation.[137] A schematic representation of HIS and NIR sorting is shown in Figure 39.

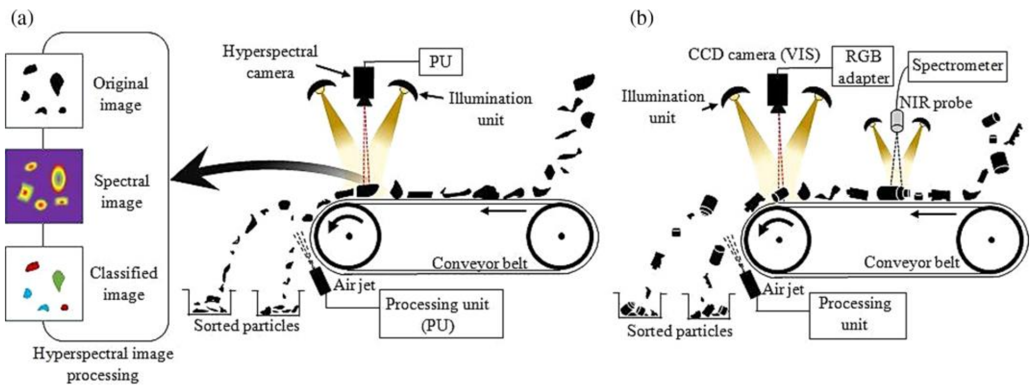

Figure 39. a) The hyperspectral sorting technique (HSI) consists of a spectral CCD camera. Waste fractions are segregated into their respective bins using compressed air nozzles. b) NIR spectroscopic sorting technique consists of a CCD camera and NIR spectrometer[137].

In the HSI sorting system, the waste is transported underneath the monitoring area and the spectral CCD camera acquires spectral data continuously at a fixed frequency. Data pre-processing and reduction is carried out, after which a classification algorithm is applied to the spectral data to perform material classification. Finally, materials are segregated from waste by compressed air nozzles depending on the data from the classification analysis.[137]

Some reported limitations are[137]:

- HSI fails to classify stainless steel if it has the same spectral information with other non-ferrous metals, and
- VIS signal ignores material with label and surface contaminants.

Applying sensor sorting for PCB treatment

Traditionally sensor based sorting has been applied to separate plastics and certain metal fractions from waste streams. However, recently imaging and sensor methods have been studied to apply them for the identification of the surface mounted components (SMCs) on the PCB[138]. In this research by Li et al., multi-modal sensors (cameras, 3D scanners, energy dispersive spectrometers, etc.) are employed to acquire relevant information of the SMCs on the PCBs. A distinct part of the recycling system is a sophisticated subsystem consisting of a diverse information processing unit for the PCB analysis, as shown in Figure 40.

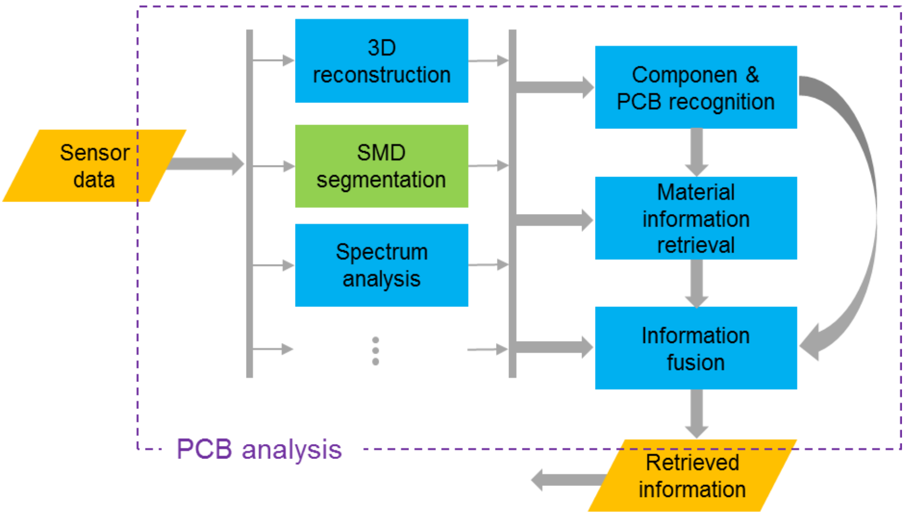

Figure 40. A schematic figure of the PCB analysis for information retrieval. (Derived from [138].)

With the information from sensors and its processing by the subsystem, the segmentation of integrated circuits (ICs) can be carried out, as demonstrated in Figure 41.

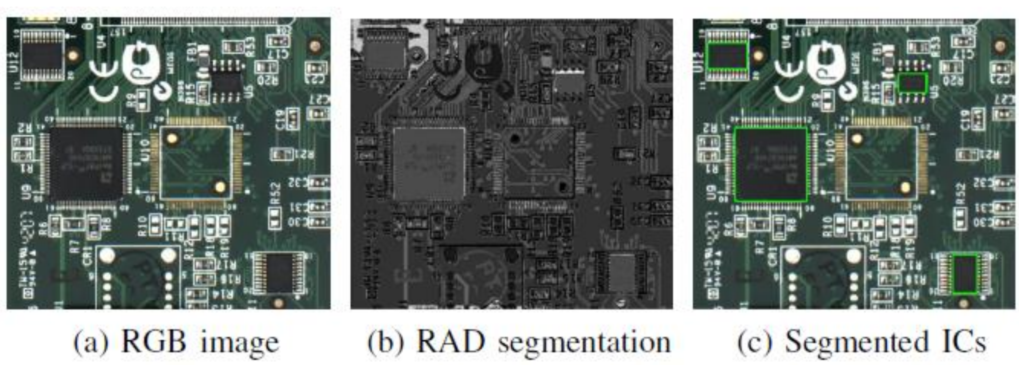

Figure 41. IC segmentation[138].

5.3.3 Monitoring/optimization

During the recent decades, a wide variety of segregation and separation technologies has been developed for waste management. Incorporating automation techniques in waste management has improved the efficiency of the sorting system. In addition to a traditional automation of devices and machines, system level automation is under development. At this level, a group of machines or workstations are interconnected or supported by material handling systems, computer and other auxiliary equipment. The operations at this level are under centralized commands. Various machines like comminution, inspection, material handling and separation systems are coordinated for an efficient automated material handling, detection, separation and discarding.[137]

The number of publications in the field of MSW treatment automation published during the last decade are seen in Figure 42.

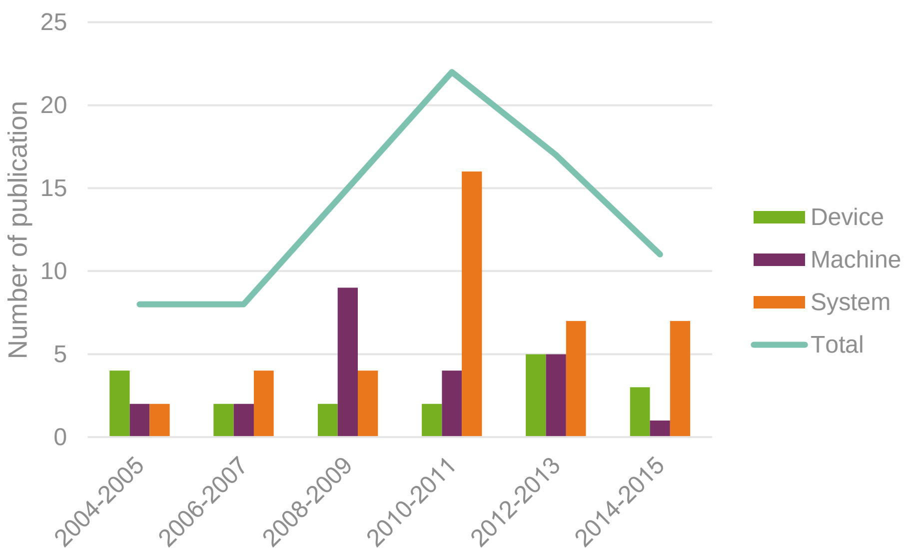

Figure 42. Number of publications versus the year of publication. (Derived from [137].)

From Figure 42 it can be noticed that the number of publications about the system level is larger than number concerning the other two levels. In addition, a growth in the system level publications has occurred under the recent years, which describes the growing interest of researchers to move from machine and device level approach to fully automated systems.[137] However, this requires open data between machines, sensors and process control, which may create pressure for different machine manufacturers to open their data for others to use.

5.3.4 Integration of treatment methods

Beside automated disassembly and sensor sorting, assistance of heat treatment on the PCB, to remove surface mounted components, has been investigated recently[139,140]. In these technologies, heat is applied on the PCBs by an infrared heater, after which solders and components are separated with an air knife or a mechanical steel brush from the PCB-board. The main target is to separate components either for reuse or for recycling separately from the PCB-board.

In addition to infrared heater, other type of methods has been applied to electronic component (EC) removal/dismantling from PCB. The two step process first damages the solder joints between EC and PCB. This is carried out either by grinding, dissolving by chemical reagents or melting by electronic heating tubes, hot air or hot fluids such as diesel, paraffinic oil and silicon oil. In the second stage an external force is applied to make ECs dislodge from PCBs, including mechanical sweep, gas jet, and centrifugal force.[141]

However, these methods requires accurate safety and environmental measures in order to avoid the generation of toxic fumes and dusts.

6 Future aspects an challenges

6.1 Integration of waste streams and their challenges

Recycling and waste management are highly influenced by regulation, through various directives with different scopes. In future, especially the potential broadening of the scope of the existing Ecodesign Directive (2009/125/EC) to include durability, recyclability, reusability, recoverability, repairability and lifetime may have a significant influence on the design of electronic products and, change the characteristics of waste flows and thus also the business conditions. In 2015, the Commission gave the European standardization organization (CEN) a mandate to develop generic standards to cover eco-design requirements related to material efficiency aspects.

Traditional products (e.g. construction products, consumer products) including electronic parts are today entering the market. As an example, sensors attached to products for e.g. enabling identification, monitoring. These new products such as electrical clothes have not been previously categorized as WEEE. Clear guidance on how these types of new waste items are to be categorized and further treated does not yet exist. In the case of electrical clothing, it has been discussed in the literature whether the electrical clothing would find their way to recycling schemes as e-waste. In addition, possible rejection of electrical clothes in collection due to the inexplicit definition in WEEE directive, technical problems in the treatment such as jamming of crushers would presumably occur.[142] Similar challenge can be expected with packaging containing electrical components. Further on, due to the increase of smart housing, electrical applications and components are expected to occur to larger extent in construction and demolition wastes, which may also require clearer guidance and description in legal framework.

Especially for the improvement of ELV recycling – separation of automotive electronic components (primarily circuit boards and rare earth magnets) from ELVs before shredding – has been discussed in Germany. This requirement for separating the electrical components before final disposal may also apply to other product streams. The application can refer to previous examples i.e. smart clothing, smart housing, and electrically equipped packaging. In addition, possible new requirements in eco-design may take this into account for example in the form of requiring detachable electrical components in applications.

As a conclusion, in future, guidance for the legislative interpretation is required in unclear situations with new applications containing electronics entering in the end-of-life stage. Clarification is required, since the targets and objectives in directives vary, as well as the responsible actor for the waste stream in question. For example, the extended producer responsibility (EPR) schemes are industry specific.

6.2 Future aspects in WEEE composition - new materials

Table 10 presents a summary of the future trends in electronics manufacturing and how they are linked to treatment of WEEE.

Table 10. A summary of future trends in both composition and treatment of WEEE.

Treatment technology/ composition factor	WEEE composition aspects	Dismantling	Size reduction	Separation
Miniaturization	• Less valuable material per component • Component size	• Robotic dismantling may have difficulties to separate parts composed of miniaturized components • Method for dismantling a miniaturized component itself is still lacking	• No major effect if the selectivity of the miniaturized components is not required	• Method for the separation of miniaturized components from each other is lacking • Separation of parts composed of miniaturized components is possible • Some particle size requirements of the sorting equipment can hinder the separation
Integration	• Different materials combined together (e.g. plastics and metals)	• Dismantling integrated components/parts difficult if the integration is carried out in a fixed way	• Integration may decrease the liberation degree of parts and elements, especially if the integration is fixed • Electrodynamic fragmentation may break the integrated components from each other if they are made of different materials	• Separation efficiency will decrease if the liberation degree decreases
Printed manufacturing	• Materials laminated/printed on the surface of the other materials	• Depending on the attachment method of the printed electronics on the appliances, it may be dismountable • Dismantling components from surface of the printed laminate unlikely	• Depending on the attachment method of the printed electronics on the appliance, decrease in liberation degree within traditional crushing methods is possible • Electrodynamic fragmentation may break the printed electronics from the appliance if they are made of different materials	• Separation efficiency will decrease if liberation degree decreases • Possibility of printed electronics ending in the light fraction

3D printing	• Less separate PCBs • Integration? • Continuous one material (complex?) parts	• Dismantling integrated components or parts difficult if the integration is fixed • Complex structure may hinder the dismantling efficiency	• If materials are integrated in the 3D printing the liberation degree of parts and materials may decrease in the crushing • Electrodynamic fragmentation may break the 3D printed structure if it composes of different materials	• Separation efficiency will decrease if liberation degree decreases • Complex structure and shape of particles may hinder the separation efficiency
Sensors	• Sensors will be used in various new products entering WEEE recycling (e.g clothes, packaging)	• If sensors are integrated in a fixed way their dismantling from application may be difficult • Robotic dismantling is focused on rigid appliances; therefore, textile may require another type of dismantling (manual?)	• Depending on the appliance sensors are attached to, different types of crushing mechanisms may be required (textiles vs. mobile phone)	• If a sensor is removed from the material during the size reduction, separation is possible • Some particle size requirements of the sorting equipment can hinder the separation
VR (virtual reality)	• Demand for display technology • Wireless network requirements of the appliance	• Robotic dismantling may cope with the dismantling procedure of displays if the design is not based on a fixed integration • The larger and more separate parts the better for dismantling	• Depending on the VR appliance, different type of crushing mechanism may be required (flexible display vs. rigid mobile phone)	• Depending on the component/material liberation in size reduction, separation processes may cope with the VR appliances
Active fasteners (design)	• No direct compositional affect but change in the crushing mechanism and liberation behaviour -> improvement in the separation efficiency	• Together with activation, dismantling efficiency (duration & degree of separation) can be improved -> more pure parts/components faster	• Increased liberation degree is expected with active fasteners since connections between parts/components/materials break in a more controlled manner • May increase the particle size in a successful liberation	• Better liberation of parts/components/materials improves separation efficiency • Possible increase in the particle size reduces the losses to fine fractions

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