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Implementation of the WEEE-directive — economic effects and improvement potentials for reuse and recycling in Germany

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Abstract Reducing the quantity of waste for disposal and saving natural resources were main drivers for the introduction of the European Directive on waste electrical and electronic equipment (WEEE-directive). This policy focused on an extension of the producer responsibility (EPR) to the end-of-life-phase of their products. Because of the EPR concept, the national transposition of the WEEE-directive, especially the German transposition in the law ElektroG, caused changes in the organisation and material flows that are sometimes not in line with the aim of the directive, which is to enforce the waste management premise "avoidance prior recycling prior disposal". Thus, the objective of this contribution is to analyse and compare the situation before and after implementation of the ElektroG in Germany, and deduce improvement potentials. Therefore, a co-operation of a municipality and a nearby disassembly company in Germany is analysed and evaluated, taking into account material flows and costs before/after implementation of the ElektroG, as well as degrees of freedom. Based on this analysis, recommendations are deduced for political decision makers and actors of the WEEE treatment system.

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1 Introduction

A key requisite for sustainable development is that the current open-loop economies are left behind and closed-loop economies are achieved. Thus, production processes are to be supplemented by reduction processes, i.e. by return and recirculation of obsolete products [1]. Due to the increase of waste, political decision makers in many countries reviewed available policy options and concluded that an extension of the responsibility of the producers to the end-of-life-phase of their products can relieve environmental pressures arising from these waste streams. Hence, the concept of extended producer responsibility (EPR) was introduced, and producers now have to accept economic and/or physical responsibility for the treatment or disposal of their own products at the end of the products' life. Through the implementation of the EPR concept, incentives for waste prevention, a promotion of product design for environment and a support of public recycling should be achieved [12].

Lindqvist distinguishes five different forms of responsibility, which may be implemented under an EPR scheme [8]:

- Liability for the proven environmental damages caused by the product extended to the end-of-life phase
- Economic responsibility also for the collection, recycling or final disposal of the manufactured products

- Physical responsibility for the management of products in their end-of-life phase
- Ownership retained by the producer and, thus, a direct link to the environmental impact of the products
- Informative responsibility by the obligation to supply information on the environmental properties of the product

As one of the first waste streams, waste electrical and electronic equipment (WEEE) has been recognised as problematic from an environmental point of view, since quantities of WEEE are growing each year all over the world and are expected to rise to 95 million tons in 2010 if current development trends persist [11]. Many countries, such as Korea, Japan, some states of the USA, and China, have introduced an implementation of EPR concepts for WEEE in particular, and many countries plan to follow. Political decision makers in the EU led the way for the introduction of a sector-specific EPR-based policy for WEEE by passing the Directive 2002/96/EC on WEEE-directive on January 27th, 2003 [3].

Within the WEEE-directive, three of the five forms of EPR, the economic, physical and informative responsibility, were implemented. Thereby, the objective of the WEEE-directive states "as a first priority, the prevention of WEEE, and in addition, the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste" ([3]: Article 1). Due to an extension of the usage phase and, thereby, the substitution of a new product, reuse can be seen as a form of avoidance. Authors such as Rose [13] and Kaebernick et al. [6] agree on this ranking and see the reuse of products and components advantageously from an ecological point of view in comparison to the recovery of materials and energy.

The transposition of the WEEE-directive in the EU led to different national implementations. Especially, different types of the EPR were realised by the EU countries, which resulted in various operative and economic structures. An analysis of the implementations of the WEEE-directive in the European countries is presented by Magalani and Huismann [10]. The authors describe and compare the financing models of the different compliance schemes. Thereby, general recommendations for the implementation of EPR-based policies are drawn. However, detailed operational issues and improvement potentials for WEEE treatment and reuse cannot be drawn by such a general study. Instead, country-specific analyses are necessary. Through this, impacts of such policies can be discovered and analysed.

Therefore, detailed analyses of material flows are presented within this contribution focussing on the situation in Germany. In Germany, the WEEE-directive was implemented by the legal Act Governing the Sale, Return and Environmentally Sound Disposal of Electrical and Electronic Equipment (ElektroG) [2]. An analysis of the impacts of the ElektroG is important for German political decision makers, since several degrees of freedom exist in terms of the further development of the regulatory system. Moreover, the assessment of such effects is of high relevance for companies operating in this framework, e.g. public waste management authorities (PWMAs) and disassembly companies. Although resulting recommendations might not be valid for all other countries, some aspects and suggestions might be interesting globally. Especially, countries that are currently about to develop and implement EPR-based legal frameworks, e.g. the USA or China, might obtain important evidence.

Against this background, the objective of this paper is the analysis and comparison of influences of the ElektroG on the performance of the WEEE treatment system, especially concerning the premise avoidance prior recycling prior disposal. Therefore, the differences in cost and revenue structures of collection, transportation, reuse and recycling processes before and after the implementation of the ElektroG are assessed based on a case study. Altogether, three scenarios are analysed:

Scenario 1	situation before the implementation of the ElektroG
Scenario 2	current situation—recycling and recovery within the framework of the ElektroG
Scenario 3	potentials arising from the degrees of freedom of the ElektroG

The contribution is structured as follows. In Section 2, a general description of the WEEE treatment system is given, analysing actors as well as processes of WEEE recycling in Germany. Afterwards, the situation before and after the implementation of the ElektroG, as well as degrees of freedom within the ElektroG are discussed in Section 3. Based on this, organisation and material flows are analysed within a case study regarding a municipality and a disassembly company in Germany. The analysis is executed for the former, current and potential WEEE treatment, and an evaluation of resulting costs and revenues is carried out for these three situations (Section 4). Upon the case study, a comparison of the scenarios is given in Section 5. The paper ends with recommendations for political decision makers and actors within the WEEE system in Section 6.

2 German WEEE treatment system

Within the WEEE treatment system, the activities acquisition and collection, transportation, sorting, and disassembly of products, as well as storage and selling of material fractions, are carried out. First, a general overview on the WEEE treatment system in Germany is given. Second, cost structures within this system are described.

2.1 Description of the German WEEE treatment system

Collection of the discarded products is primarily organised by PWMAs. Smaller WEEE amounts are also collected by retailers, producers or disassembly companies. After collection, products are transported to disassembly companies, which can either be private companies or socially subsidised firms. At these companies, processes for reuse of products and components (e.g. testing and resale), as well as processes for material recycling (e.g. gaining of valuable materials and removal of harmful substances) are performed.

With regard to collection, transportation, and treatment processes, a separation into products and components for reuse and devices for material recycling is necessary [9]. The main reason for this is that products for reuse need to be transported in a value-conserving way. This means that small boxes should be used, and manual packing and un-packing of these boxes is necessary. By contrast, devices for material recycling can be transported in large containers. These containers are emptied by dumping (Fig. 1). This handling results in a destruction of products, if not already during transportation then during unloading at the latest.

Products for reuse need to be tested at the PWMA or at the disassembly company. After functional testing and subsequent sorting, reusable products can be provided to a secondary market for direct reuse or remanufacturing, i.e. products are sold to resellers or retailers, or directly to consumers. Moreover, non-destructive disassembly can be applied at the disassembly company in order to obtain reusable components.

Fig. 1 Value-conserving vs bulk transportation (value-conserving logistics: own pictures, bulk logistics: [17])

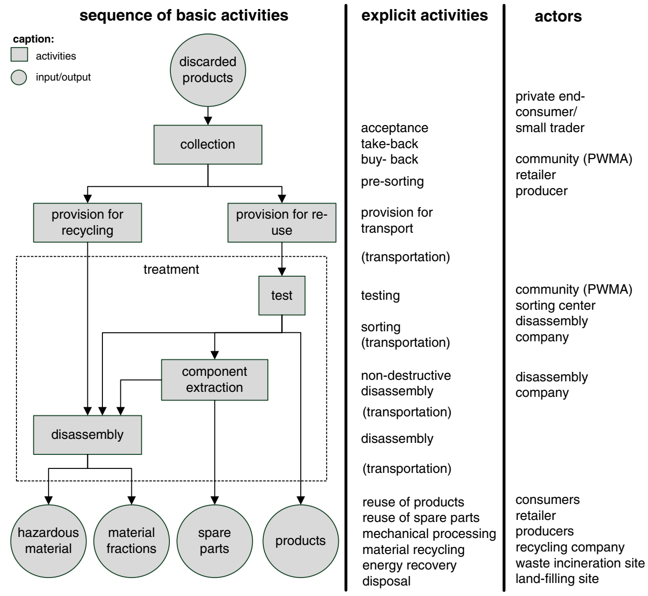

Fig. 2 Activities for WEEE recycling and reuse

Extracted components can be sold as spare parts to consumers, retailers or resellers. In case of take-back for a producer, products are also sold to producers.

Within material recycling, products are disassembled in order to gain valuable material fractions and to remove harmful substances. Resulting tradable material fractions of defined quality are sold to recycling companies for further mechanical processing, e.g. metal fractions are supplied to metal or steel works [19]. Other material fractions have to be disposed of in landfills or sent to incineration. An overview of activities and actors in the WEEE treatment system is given in Fig. 2.

2.2 Economic structure of the German WEEE treatment system

In the following, costs for collection, transportation and treatment of products and materials, as well as revenues/costs for sale of material fractions, are described. Due to the different transportation modes and processes, costs and revenues for reuse of products and recycling of materials differ. During collection, costs occur at the PWMA for collection and provision to further recycling activities. Here, additional costs emerge if a pre-sorting of products for reuse is carried out, since additional space for the many boxes for value-conserving transportation is needed and employees might spend more time within the collection process due to monitoring the products with regard to reusability.

If a value-conserving transportation to the disassembly company takes place, transportation and handling changes (e.g. kind of containers or boxes, loading, unloading processes). Altogether, costs for a value-conserving transportation are usually higher than costs for bulk transportation. After value-conserving transportation, products are tested with regard to their reuse potential.

Treatment and component extraction cause disassembly costs. Disassembly costs for products, which were transported with a value-conserving transportation mode are usually higher than disassembly costs for products within the bulk stream, since products already get destroyed with bulk transportation, e.g. the chassis breaks and, thus, disassembly is already partly performed. However, bulk transportation might also have disadvantages for treatment, since entire batches can be contaminated if hazardous material is set free. Moreover, harmful substances can be released to the environment.

Revenues are generated by sale of reusable products and components, as well as sale of valuable materials. Costs occur for sending hazardous or non-valuable materials to landfills and incineration. Over time, sales revenues vary usually stronger than costs, since revenues for material fractions are tied to global primary resource markets, which might change from day to day.

The three alternatives (product reuse, component extraction, material recycling) substitute each other. If a product is reused, neither material fractions nor components can be gained. If components are extracted, reuse of the complete product is no longer possible, and only a part of the materials remain for recycling. If materials are recycled, neither product reuse nor component extraction can be accomplished. Due to different material values of each product and component, different material values during treatment are obtained if products or components are reused. Such coherences are displayed in Fig. 3 for a collection of large household appliances, e.g. washing machines, fridges and freezer. Here, edges symbolise the flow of products, components or materials. Masses related with these flows differ concerning the products, components and materials regarded. Moreover, some flows might be zero.

Based on this figure, interdependencies between material recycling and reuse can be explained. Washing machines contain some hazardous materials and a high amount of valuable materials, e.g. steel. Freezers and fridges contain even more hazardous material, and thus cause higher costs during treatment. If all large household appliances are collected and treated, the material value can be determined depending on the relation between freezers/fridges and washing machines in the collection. Hence, if a high number of washing machines and a low number of freezers/fridges are collected, the material value of the entire collection is high (e.g. positive), while the material value is lower if the relation is vice versa (e.g. negative). If products with a high material value are reused instead of recycled, the described relation of products for treatment and, hence, the material value changes. Therefore, if reuse is carried out, revenues from reuse must cover resulting losses from material value.

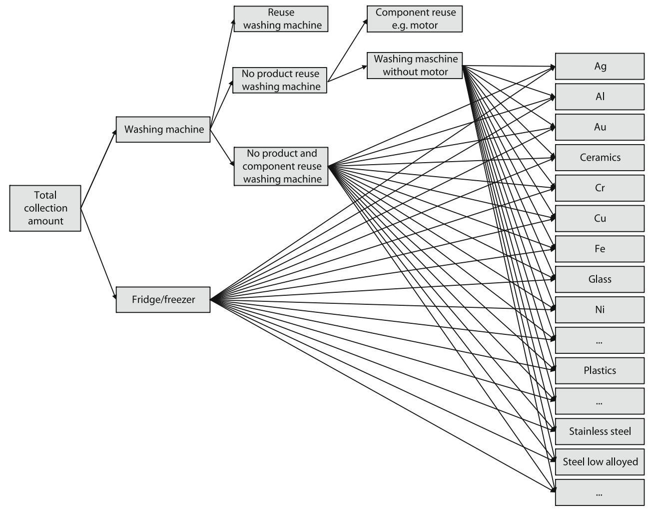

Fig. 3 Collection, product, component, material fraction coherences

3 Operating and economic structure in Germany before and after ElektroG

The implementation of the ElektroG had an essential impact on the operation and economic structure of the treatment of discarded electronic products. Since operational issues are impeding or amplifying the WEEE treatment and reuse, and these effects are related to the initial situation and the changes related to the introduction of the ElektroG, a detailed analysis of material flows before and after the introduction of the ElektroG is needed. Moreover, further investigations are needed concerning degrees of freedom within the law. Hence, three scenarios are analysed. First, the former situation and organisation of WEEE treatment before the implementation of the ElektroG is regarded. Second, resulting changes due to the implementation of the ElektroG in Germany are analysed. Third, existing degrees of freedom in the national adoption of the German ElektroG are explored.

3.1 Situation before the implementation of the ElektroG in Germany

Before implementation of the ElektroG, consumer electronics were collected by the PWMA and usually recycled by a contracted disassembly or recycling company. However, there was no obligation to dispose these products separately from the municipal waste stream. Due to this fact, many small items were not collected for WEEE treatment.

The disassembly of consumer electronics was mainly performed by independent disassembly companies, which were processing electronic products of all types and all manufacturers. Many of these companies processed less than 1,000 tons of electronic scrap per year [19]. Furthermore, a large number of social enterprises were engaged in electronics disassembly. These publicly subsidised institutions offer jobs and training programs for disabled and long-term unemployed and, thereby, contribute to social and environmental development the same time [20].

Long-term supply agreements between PWMA and disassembly companies were common [19]. Thereby, the circa 440 German PWMAs assigned these long-term contracts decentralised [18]. Due to advantages, especially concerning transportation costs, contracting was done by many PWMAs with regional companies. Accordingly, regional networks were widely present.

Owing to product complexity of WEEE and the multitude of existing product categories, types, variants and after-usage states, disassembly was mainly performed manually [19]. Within the regional network, collection, storage and transportation processes were agreed upon to meet the requirements of the succeeding processes. In most regional networks, the succeeding companies (e.g. disassembly company) provided containers and transportation devices to ensure an appropriate handling. Hence, not only bulk transportation but also smaller vessels, especially lattice boxes, were used to ensure value-conserving transportation for some product types. At disassembly companies, products were separated into material fractions or reusable components. Although it is often stated that reuse of products or parts collected from private households is inapplicable due to the advanced age and low value [7], up to 10% of the discarded products and their components were reused before the implementation of the ElektroG [9].

Revenues were obtained by recovering valuable material fractions, e.g. metals. Additionally, disassembly companies obtained revenue through the reuse of products and components. On the contrary, costs occurred for fractions that needed to be disposed of and for fractions, where the recovery process caused more costs than revenues could be obtained through sales. This is especially the case for the material fraction glass, for all fractions similar to domestic waste and for fractions requiring special supervision [18].

If costs for transportation, disassembly, recycling and disposal of electric and electronic products exceeded revenues, the PWMA had to pay the disassembly company for recycling. PWMAs financed their operations by waste management fees that consumers (last owners) were charged with when returning products. Financial flows between PWMA and disassembly company were product-specific. In case of large appliances, financial flows were defined upon the number of products. For small appliances in containers, mass-specific financial flows were applied.

3.2 Current situation with implementation of the ElektroG in Germany

With the implementation of the ElektroG in Germany, systems to take back electronic products are installed. Collection targets and recycling and recovery targets are introduced and have to be fulfilled. The responsibility of producers is expanded beyond the usage phase of products onto the treatment of discarded electronic devices at the end of the product's life.

Since the producer has to be able to fulfil his tasks nationwide, disassembly contracts are now no longer awarded in a decentralised way by every single PWMA, but centralised by producers or even consortia of producers. Producers, for instance, cooperate in networks, e.g. the European Recycling Platform, in order to have a better basis for negotiations with waste management companies [14]. This leads to an enhanced centralisation of treatment [19]. In order to preserve the decentralised treatment system that existed before the implementation of the ElektroG, small- and medium-sized disassembly and recycling companies now cooperate in recycling networks [4], e.g. Recycling Network Europe (RENE). WEEE is still collected by the PWMA. The ElektroG differs from the EU directive by grouping the ten WEEE-directive product categories into five ElektroG collection groups and the PWMA needs to sort discarded products accordingly (Fig. 4). In order to organise the pick-up processes and to control collection, recovery and recycling targets, the Foundation Elektro-Altgeraete-Register (EAR) was established. Thus, PWMAs order the pick-up of a collection group, if at least 30 m^3 of one collection group accumulates at the PWMA ([2]: ElektroG §9(4)). The EAR then determines a producer based on certain criteria, which is then responsible for the pick-up and

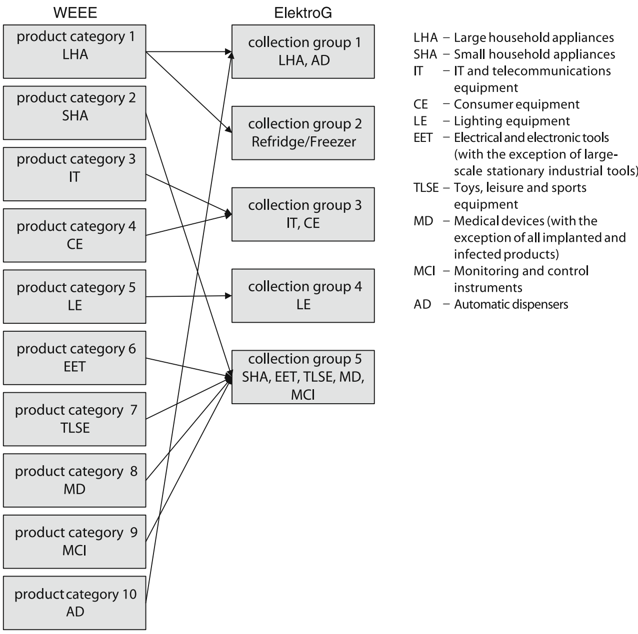

Fig. 4 WEEE categories and ElektroG collection groups

treatment of the collected devices and for provision of a new container. Since producers usually outsource these tasks, the pick-up and treatment of collected devices is organised by a commissioned service provider, e.g. a recycling network.

As this description shows, decentralised regional networks consisting of PWMAs and disassembly companies no longer exists. Instead, different transportation and disassembly companies pick-up products at the PWMA. Thus, an equal container size is necessary in order to allow for such a flexible and varying system to work. Hence, four of the five collection groups (exception is group 4: gas discharge lamps) are usually collected in large, 38 m^3 containers. Doing so, a cost-optimised bulk flow results. However, these optimised logistic processes lead to a decrease of WEEE quality at the gate of disassembly companies, since value-conserving transportation is no longer possible. Thus, reuse of products after such transportation is almost impossible. As a result, reuse shares of the returned products dropped significantly since the introduction of the ElektroG from 10% to approximately 3% [9]. Therefore, legal requirements concerning reuse prior recycling prior disposal cannot be operationalised anymore, because of too-large container sizes and bulk flow optimised logistics.

Concerning the financial flows, private end-consumers are privileged to bring their electronic devices to PWMAs free of charge. In Germany, the collection is organised and financed by the regional PWMAs. PWMAs cover resulting cost through an additional charge on the public waste management fee. Since the producer is responsible for pick-up, transportation and further treatment, the service provider charges the producer for the fulfilment of these tasks.

3.3 Using the degrees of freedom within the ElektroG

PWMAs have the freedom to exclude entire collection groups from the treatment within the ElektroG ([2]: ElektroG $9(6)). In such a case, the PWMA inherits all tasks and obligations of the producers concerning pick-up and further treatment of the collected products. Thus, the PWMA is now responsible and has to cover all costs for the reuse of the products or components, the recycling of materials, the recovery of energy or for proper disposal. Since PWMAs are public law institutions, they have the obligation to operate at the level of lowest costs in order to minimise waste management fees charged from inhabitants of the community. Therefore, PWMAs are usually excluding a collection group only, if revenues can be obtained from treatment of this group. On the contrary, disassembly companies are interested in co-operating with the PWMA to obtain masses for reuse and treatment within their region. An exclusion of one of the five collection groups is possible for at least 1 year and is binding within this period. Exclusions must be announced to the EAR 3 months in advance and can be prolonged every year for the period of 1 year. As shown in Fig. 5, such an exclusion of a collection group is done by almost all of the 440 German PWMAs for group 1 (large household appliances except refrigerators). Moreover, every second PWMA excludes collection group 5 as well, and one fourth of all PWMAs exclude collection group 3.

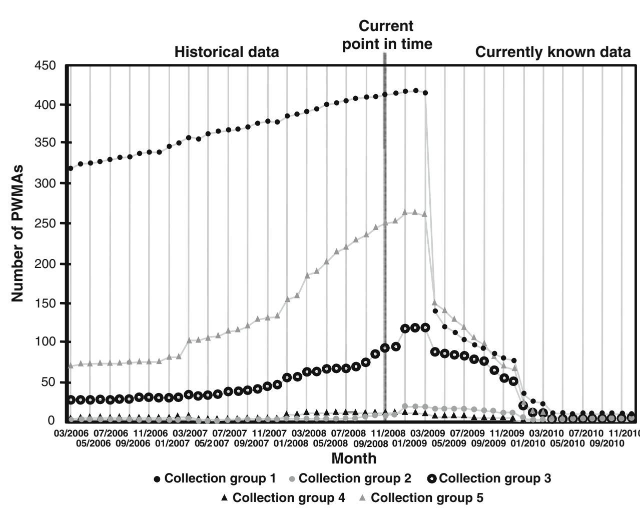

Fig. 5 Exclusions of collection groups by PWMAs over time (according to [15])

Collection groups 2 and 4 are rarely excluded. In order to ensure a proper treatment, PWMAs usually cooperate with disassembly companies as done before the implementation of the ElektroG [9]. Thus, regional networks as the ones before the implementation of the ElektroG are established again for treatment of these excluded groups. In such regional networks, value-conserving collection and transportation can be re-established, and reuse might be possible.

Since a PWMA needs to switch from less expensive bulk logistics to value-conserving logistics, bulk logistics is only repealed, if the additional costs of value-conserving logistics are covered, e.g. by reuse of products. To minimise transportation and handling costs, a close co-operation between the PWMA and the disassembly company is necessary. Hence, the disassembly company can share information with regard to reusability or other sorting criteria upon which the following processes are facilitated or additional revenue can be obtained.

As before, disassembly companies sell the valuable material fractions. Revenues need to cover the costs of the acquisition, transportation and treatment within this regional network. Additional income can be obtained through reuse of parts and products, e.g. when using engines of washing machines as spare parts. Costs occur for fractions, which need to be landfilled or disposed of.

For group 1 (large household appliances except refrigerators), high revenue can be obtained since these appliances contain a high amount of valuable materials. Concerning other collection groups (e.g. group 3 — IT, telecommunication and consumer equipment), revenues of valuable material fractions often do not cover total costs. Therefore, an exclusion of such product groups is only done if additional revenues, e.g. from selling reused products and components, are likely to cover the costs. Since additional processes like sorting and testing, as well as a value-conserving transportation, are needed to obtain reusable products and parts, further costs emerge that also need to be covered by the regional network.

4 Empirical study

Within the research project “Business Processes and Network Management in Closed-Loop Supply Chains to close Product Cycles (GeProNet)”, a regional network consisting of a PWMA and a disassembly company is regarded to analyse the effects of the implementation of the ElektroG. The focus lays on the operational issues impeding the WEEE treatment and reuse. As the transposition of the EPR and related changes in the organisation and financial responsibility of the WEEE-treatment seems to cause negative effects on reusability, the goal of the study is to identify improvement potentials and deduce recommendations for German political decision makers concerning further adjustments of the ElektroG and for other countries developing effective and efficient EPR-based environmental legislation. Against this background, changes in material flows and financial flows that arise because of the implementation of the ElektroG are analysed. Thus, the analysis covers the three scenarios: (1) situation before the implementation of the ElektroG, (2) current situation — recycling and recovery within the framework of the ElektroG and (3) potentials arising from the degrees of freedom of the ElektroG. Data for scenario calculation and comparison were obtained within an empirical case study. The co-operation between PWMA and disassembly company within the regional network is described first. Hereupon, the data acquisition within the case study is regarded. To evaluate the economic effects of the implementation of the ElektroG, a calculation is done for each scenario, upon the data on costs and revenues obtained in the case study.

4.1 Regional network description

A regional network consisting of a PWMA and a disassembly company is regarded. Within this regional network, the PWMA provides discarded products to the disassembly company. At the disassembly company, reuse and material recycling are carried out.

The PWMA operates in a catchment area of about 204 km^2 and serves as collection point for approximately 123,000 inhabitants. The distance between PWMA and disassembly company is 35 km. The disassembly company has 50 employees, focuses its activities on collection groups 1, 3 and 5, and is mainly performing manual disassembly. Next to disassembly for material recovery, the disassembly company is engaged in marketing of reusable products and components.

4.2 Data acquisition within the case study

At first, a decision had to be taken with regard to the WEEE groups upon which the analysis should be based. Therefore, the five product groups that are separately collected according to the ElektroG were analysed with help of the experience of the PWMA and the disassembly company. Group 1 (large household appliances without refrigerators) has a very high material value. Thus, this group is already excluded by most

PWMAs, and material recycling is mainly performed by the disassembly companies. Because of the large size of the products of this collection group, the transportation and handling did not change with implementation of the ElektroG. Hence, no changes because of the implementation of the ElektroG could be discovered for this group. Concerning the other collection groups 2, 3, 4 and 5, experience of the disassembly company shows that material value is often too low to cover recycling costs. For collection group 3, there is a high reuse potential, which could result in higher revenues than costs in total. However, the reusable portion of products of this group decreased tremendously with introduction of the ElektroG. Therefore, collection group 3 seemed to be very promising for showing the flaws of the new regulation and drawing improvement potentials. Since knowledge on distribution channels, as well as on criteria for reuse, were available at the disassembly company, collection group 3 was selected for the investigations in the case study.

In a first data acquisition from December 2007 to January 2008, the amount of products in collection group 3 with a potential for reuse were assessed at the PWMA in order to validate the reuse potential [5]. Thereby, four product types with reuse potential were determined: monitors, TVs, printers and desktop PCs.

For products of these types, a visual inspection was carried out at the PWMA based on minimal threshold criteria for reuse (no testing). These criteria were defined in co-operation with the disassembly company for all product types with regard to reuse market requirements. For instance, there is no reuse potential for TV sets that have scratches on the screen or that are missing certain connections like SCART. Thus, these products can go directly into bulk transportation at the PWMA. Results of the empirical study showed that 50–60% of collected electronic devices of product group 3 fulfil the basic reuse criteria based on visual inspection only, i.e. without testing. Thus, these products should be treated carefully during collection, storage and transportation [5]. Table 1 shows the shares of products with a basic reuse potential on a component level or as a whole system for the four analysed product types of collection group 3.

Based upon this first survey, further investigations were carried out concerning the changes in material flows and financial flows through the introduction of the ElektroG. Data on the following aspects are important for analysis:

- Costs for value-conserving transportation
- Costs for bulk transportation
- Treatment (disassembly) costs after value-conserving transportation
- Treatment (disassembly) costs after bulk transportation
- Material recovery revenues or costs for the entire collection group and for the potential reusable items
- Composition of the collection group concerning reusable and non-reusable items
- Reuse revenues

Table 1 Basic reuse potential of sample batch (according to [5])

Product category	Assessed amount of appliances	Reuse potential	
		Product level	Percentage
Computer monitor	519	Whole system	64%
Printer	480	Component	69%
Desktop PC	337	Component	60%
TV set	548	Whole system	52%

In order to gather these data, collection group 3 was excluded by the PWMA in May 2008 until April 2009. Upon the amount of collected product within the first 6 months of the study, a yearly amount of 374 tons of collection group 3 is calculated. This number will be used throughout the analysis and calculation in order to present values on an annual basis, which is important with regard to the economic evaluation of the exclusion from the ElektroG.

However, not all reusable products listed in Table 1 are considered for reuse within this analysis. During the first months of the study, analyses showed that the material value of monitors, printers and desktop PC components was higher than the price obtained for reuse. Therefore, these products are recycled instead of reused because of economic reasons. Hence, only TV sets could be regarded for reuse. Therefore, concerning the composition of the collection group and reuse prices, the amount of TV sets are of interest. Hence, all TV sets in the collection stream were counted. Moreover, a differentiation between large and small TV sets was done. The amount of reusable TV sets is calculated upon the data acquisition on reusability of devices from collection group 3 (see Table 1). As analyses showed, 48% of collection group 3 are TV sets, from which half of them were reusable based on a visual inspection at the PWMA. However, only 3% of the TVs (5 tons) are regarded reusable after testing at the disassembly company (see also Table 2).

Table 2 Average collection, reuse and recycling distribution (CRT TV)

	Relation to previous amount	Relation to collection amount	Exemplary mass calculation (tons/a)
Collection amount	100%	100%	374
CRT TVs	48% (in collection amount)	48%	180
After visual inspection	52% (potentially reusable CRT TV)	25%	93
After testing	5% (reusable from pre-sorting)	3%	5

4.3 Cost and revenue structure

Within the first 6 months, information for the analysis and comparison of the three scenarios was gained based on the following surveys:

- Bulk transportation vs. value-conserving transportation
- Effect of bulk transportation on disassembly costs
- Effect of value-conserving transportation on disassembly costs
- Amount of small and large TVs within the collection

For obtaining data on value-conserving vs. bulk transportation costs, different transportation devices were used during collection and transportation. Different disassembly and handling costs resulting from the transportation mode were assessed through disassembly studies.

As results of the empirical study show, transporting collected devices with bulk logistic containers costs 13€/ton, while the transportation with value-conserving lattice boxes costs 36€/ton. Moreover, the choice of applied logistics had an effect on costs of further treatment activities. After bulk transportation treatment costs of 60€/ton were observed and after transportation with value-conserving lattice boxes, treatment costs of 78€/ton were determined.

Regarding the material value of collection group 3, an average value was chosen to account for the highly volatile prices of material fractions. Hence, a material value of 50€/ton for the entire collection group 3 is used in the following.

The same accounts for the material value of TV sets. In average, 0€/ton material value can be recovered during the treatment of a TV. Since 48% of collection group 3 are TV sets, the material value of collection group 3 without the TV sets is 96€/ton.

With regard to the reuse of TV sets, a differentiation between large and small TVs is necessary, since different revenues can be obtained depending on the size of the TV. Hence, an average reuse price for TVs (€/ton) was calculated upon the internal data of the disassembly company concerning the sales prices of large and small TVs, the relation between large and small TVs in the collection, as well as their average weight. As result, an average price of 283€/ton could be obtained. Furthermore, costs for testing TV sets were calculated with 13€/ton.

Regarding the revenues that can be achieved at the market, reuse of TVs is more profitable than treatment. However, total costs for reuse are also higher than total costs for recycling. The different costs for TVs concerning transportation and recycling costs at the disassembly company, as well as revenues, are shown in Table 3. In the following, the three scenarios (1) situation before the implementation of the ElektroG (2) current situation — recycling and recovery within the framework of the ElektroG and (3) potentials arising from the degrees of freedom of the ElektroG are regarded. Investigations on the network structure are carried out.

Scenario 1 — before implementation of ElektroG. In scenario 1, the situation before the implementation of the ElektroG is regarded. Upon the description of the operating and financing structure (Section 3.1), costs and revenues are determined. Value-conserving transportation is applied for all product types with high reuse potentials. No pre-sorting concerning reusability is done at the PWMA. A pre-sorting and adjacent func-

Table 3 Different revenues (+) and costs (−) for processing and sales of collection group 3 with reuse option for TV sets

		Bulk transportation	Value conserving transportation
Activities	Transportation	−13€/ton	−36€/ton
	Testing		−13€/ton
	Treatment (disassembly)	−60€/ton	−78€/ton
Outputs	Reuse CRT TV		283€/ton
	Material fraction entire collection	50€/ton	50€/ton
	Material fraction CRT TV only	0€/ton	0€/ton
	Material fraction collection without CRT TV	96€/ton	96€/ton

tional testing is carried out at the disassembly company. Thus, it is assumed that all products with reuse potential, i.e. in our study, all TV sets, are transported value-conserving. Upon the cost, revenue and mass structures within the case study (Tables 2 and 3), the marginal income for scenario 1 is calculated (see Table 4).

Scenario 2 — current situation — recycling and recovery within the framework of the ElektroG. In this setting (scenario 2), all masses are provided for the WEEE treatment system within the framework of the ElektroG. Therefore, only bulk transportation takes place. Hence, only material recycling is carried out, which, at the same time, means that reuse is not possible. Upon the cost and revenue structures of the case study (Table 3), the marginal income is determined for scenario 2 (see Table 5).

Scenario 3 — potentials arising from the degrees of freedom of the ElektroG. In scenario 3, costs and revenues regarding the exclusion of collection group 3 are regarded. As known from the calculation of scenario 1 and 2, value-conserving transportation (scenario 1) is much more expensive than bulk transportation (scenario 2). Moreover, reuse cannot cover these additional transportation costs (scenario 1). Hence, an exception of collection group 3 can only be economically feasible if PWMA and disassembly company reduce costs. Therefore, a close co-operation is regarded, in which pre-sorting takes place at the PWMA. Testing still occurs at the disassembly company. The calculation is presented in Table 6.

Thus, 93 tons of the 374 tons collected are sorted based on visual inspection for value-conserving transportation. Therefore, 281 tons are transported with bulk transportation. After transportation, only 5 tons

Table 4 Costs and revenues for scenario 1

	Costs (€/ton)	Revenues (€/ton)	Amount (tons/a)	Value (€/a)
Transportation bulk	−13		194	−2,522
Transportation value-conserving	−36		180	−6,480
Testing	−13		93	−1,209
Treatment after bulk transportation	−60		281	−16,860
Treatment after value-conserving transportation	−78		175	−13,650
Total costs (activities)				**−40,721**
Revenue reuse		283	5	1,415
Material fractions (collection group 3)		50	0	0
Material fractions (TV)		0	175	0
Material fractions (collection group 3 without TV)		96	194	18,624
Total costs and revenues (output)				**20,039**
Marginal income				**−20,682**

Table 5 Costs and revenues for scenario 2

	Costs (€/ton)	Revenues (€/ton)	Amount (tons/a)	Value (€/a)
Transportation bulk	−13		374	−4,862
Transportation value-conserving	−36		0	0
Testing	−13		0	0
Treatment after bulk transportation	−60		374	−22,440
Treatment after value-conserving transportation	−78		0	0
Total costs (activities)				**−27,302**
Revenue reuse		283	0	0
Material fractions (collection group 3)		50	374	18,700
Material fractions (TV)		0	0	0
Material fractions (collection group without TV)		96	0	0
Total costs and revenues (output)				**18,700**
Marginal income				**−8,602**

Table 6 Costs and revenues for scenario 3 (testing at disassembly company)

	Costs (€/ton)	Revenues (€/ton)	Amount (tons/a)	Value (€/a)
Transportation bulk	−13		281	−3,653
Transportation value-conserving	−36		93	−3,348
Testing	−13		93	−1,209
Treatment after bulk transportation	−60		281	−16,860
Treatment after value-conserving transportation	−78		88	−6,864
Total costs (activities)				**−31,934**
Revenue reuse		283	5	1,415
Material fractions (collection group 3)		50	0	0
Material fractions (TV)		0	175	0
Material fractions (collection group without TV)		96	194	18,624
Total costs and revenues (output)				**20,039**
Marginal income				**−11,895**

Table 7 Costs and revenues for scenario 3 (testing at PWMA)

	Costs (€/ton)	Revenues (€/ton)	Amount (tons/a)	Value (€/a)
Transportation bulk	−13		369	−4,797
Testing	−13		93	−1,209
Transportation value-conserving	−36		5	−180
Treatment after bulk transportation	−60		369	−22,140
Treatment after value-conserving transportation	−78		0	0
Total costs (activities)				**−28,326**
Revenue reuse		283	5	1,415
Material fractions (collection group 3)		50	0	0
Material fractions (TV)		0	175	0
Material fractions (collection group without TV)		96	194	18,624
Total costs and revenues (output)				**20,039**
Marginal income				**−8,287**

of the 93 tons pass the testing. This leaves 88 tons for treatment after value-conserving transportation.

As an alternative, the network setting within the regional network can be changed. For example, a testing could take place before transportation at the PWMA. If this could be established, value-conserving transportation between PWMA and disassembly company could be avoided for 88 tons. This leads to cost depletion of 3,608€ during transportation and treatment. Results of this new network setting are displayed in Table 7.

5 Comparison

Different costs and revenues arise in each scenario depending on collection, transportation, disassembly and sale of products, parts and fractions of the different collection groups. Upon the calculation of costs and revenues for the three scenarios in Section 4, a comparison can be done to examine the changes in economic and ecologic performance due to the implementation of the ElektroG.

Concerning the ecologic performance, the fulfilment of the waste avoidance premise is regarded. With respect to the economic performance, overall costs are significant. For exploiting the economic potentials of reuse, the distribution of the costs between the actors plays an important role. Table 8 gives an overview on the costs and revenues, as well as the economically responsible actors of the three scenarios.

As can be seen in all of the scenarios, no positive marginal income can be achieved. Hence, one of the actors in the system has to pay for recycling activities. When comparing the scenarios, differences arise with regard to the amount that has to be paid in total, as well as to the spread of costs and revenues among actors.

Highest costs resulted before implementation of the ElektroG (scenario 1) because of high amounts of products that were transported in a value-conserving way. However, a reuse of products was possible due to the value-conserving transportation from an environmental point of view. In this scenario, communities had to finance the collection and treatment. Since the treatment for material recycling was paid by the community, the disassembly companies only had to cover costs for testing and reusing products or extracting components.

Table 8 Scenario comparison

Actors	Scenario 1			Scenario 2			Scenario 3		
	Before ElektroG			With ElektroG			Exclusion from ElektroG		
	C (€/a)	N (€/a)	P (€/a)	C (€/a)	N (€/a)	P (€/a)	C (€/a)	N (€/a)	P (€/a)
Collection	X			X			X		
Transport (bulk)	−2,522					−4,862		−4,797	
Treatment (bulk)	−16,860					−22,440		−22,140	
Material	18,624					18,700		18,624	
Transport (value-conserving)	−6,480							−180	
Test		−1,209						−1,209	
Treatment (value-conserving)	−13,650							0	
Reuse		1,415						1,415	
Result per actor	**−20,888**	**206**	**0**	**0**	**0**	**−8,602**	**0**	**−8,287**	**0**
Result per scenario		**−20,682**			**−8,602**			**−8,287**	

C - Community (waste management fee at PWMA)
N - Regional network (PWMA, disassembly company)
P - Producer
X - Costs, amount irrelevant since they are the same for each scenario

Thus, reuse was economically feasible for disassembly companies.

Applying the ElektroG (scenario 2), fewer costs arise in total since all products are transported and treated with bulk logistics. Accordingly, neither value-conserving transportation nor reuse is applied. In Germany, the community still has to finance the collection, while the producers are responsible for covering all costs arising for transportation and treatment of discarded products. If PWMAs exclude a collection group, as is exemplarily done in scenario 3, the PWMA has to organise and finance the transportation and treatment of WEEE. Therefore, PWMAs build regional networks with disassembly companies. As results show, this is the most preferable scenario from an economic point of view. Lowest total costs result, if pre-sorting is carried out at the PWMA. Moreover, the waste management premise is fulfilled, since reuse of products is carried out. However, the resulting regional network of PWMA and disassembly company now has to cover the costs and split the revenues.

Although this situation is, in total, economically and ecologically preferable, it will not be implemented since the network cannot work profitably. Total costs are lower compared to both of the other scenarios, but local cost for PWMA and disassembly company are higher than the treatment within the framework of the ElektroG (scenario 2).

6 Recommendations

With the implementation of the ElektroG in Germany, the aim was to achieve an economical and ecological preferable solution for the recycling of WEEE. Consequently, as the results of this study show, regional networks with reuse activities should have been aimed for. However, current analyses show that reuse of products decreased tremendously with implementation of the new legal framework. Hence, improvements of the ecologic performance, thus for reuse, are necessary.

Therefore, recommendations for political decision makers are conducted for the further development of the regulatory system. Moreover, the recommendations presented in the following might help political decision makers in other countries concerning the development or adjustment of their regulatory system as well.

While the ecologic performance should be improved, the economic situation should not be deteriorated. Hence, a return to the situation before the implementation of the ElektroG is not preferable, since it causes the highest costs. The implementation of the ElektroG should also not be retained as presently implemented. Bulk transportation causes the destruction of ecologic potential. Therefore, value-conserving transportation is a part of the solution.

If value-conserving transportation is prescribed for all product types with reuse potential, a fulfilment of the legal requirements concerning non-destructive collection and transportation would occur. Consequently, legal requirements concerning the premise could be operationalised. On the contrary, high costs would emerge comparable to the setting before implementation of the ElektroG.

The pre-sorting of discarded electronic products at the PWMA in products for reuse and products for recycling could lead to ecological improvements since reuse activities are possible. However, pre-sorting

Table 9 Comparison of the recommendation with scenario 2 and 3

Actors	Scenario 2			Scenario 3			Recommendations		
	With ElektroG			Exclusion from ElektroG					
	C (€/a)	N (€/a)	P (€/a)	C (€/a)	N (€/a)	P (€/a)	C (€/a)	N (€/a)	P (€/a)
Collection	X			X			X		
Transport (bulk)			−4,862		−4,797				−4,797
Treatment (bulk)			−22,440		−22,140				−22,140
Material			18,700		18,624				18,624
Transport (value-conserving)					−180			−180	
Test					−1,209			−1,209	
Treatment (value-conserving)					0			0	
Reuse					1,415			1,415	
Result per actor	**0**	**0**	**−8,602**	**0**	**−8,287**	**0**	**0**	**26**	**−8,313**
Result per scenario		**−8,602**			**−8,287**			**−8,287**	

C - Community (waste management fee at PWMA)
N - Regional network (PWMA, disassembly company)
P - Producer
X - Costs, amount irrelevant since they are the same for each scenario

should only be done if reuse follows. In scenario 3, this economic and ecologically preferable situation is described. As shown in Table 7, testing should occur at the PWMA prior to transportation to the disassembly company, only in this case, a better economic solution than the current WEEE treatment can be obtained. Due to the financing structure, this cannot be accomplished.

Hence, the financial flows need to change. Therefore, political actors should strive for allowing a separation of discarded products from the bulk stream at the PWMA and, moreover, propose testing at the PWMA for this separation rather than a pre-sorting. Thereby, the producer's responsibility would still cover the recycling of WEEE, but the amount of WEEE would be reduced by the share of reusable products. This proposed financial flow, when separating collected products with reuse potential at the PWMA but leaving the producer economically responsible for the resulting bulk stream, is only possible if only the reusable products are excluded from the system. This practice is currently regarded as forbidden in Germany, since all collected WEEE is within the ownership of the producers responsible for further treatment. Currently, there is a discussion with regard to the interpretation of legal regulations questioning the priority of ownership of producers. In Thärichen/Prelle [16], inspection and identification of reuse potential is regarded as changing the equipments' legal status from "waste" to "product" and, thereby, allowing a separation from the bulk stream. If these legal discussions lead to an admission of separation, pre-sorting could occur at the PWMA. Hence, a pre-requirement for reuse would be fulfilled, and moreover, these pre-sorted products could be tested and prepared for reuse within regional networks.

Actors within regional networks should strive for close co-operations, e.g. testing at PWMAs rather than at disassembly companies. As shown, this will reduce costs as value-conserving logistics will only be applied to reusable products. Hence, the profitability of reuse will increase. Table 9 shows the recommended distribution of the costs between the actors.

This cost distribution represents a win–win situation for all actors involved. Within the regional network, revenues can be obtained. The producer needs to pay less for transportation and treatment, and thereby, a solution with minimal costs can be achieved. Additionally, the premise "avoidance prior recycling prior disposal" is fulfilled. Hence, producers, PWMAs and recyclers, as well as policy makers, should work towards the implementation of the outlined approach.

The presented study outlines potentials for reducing costs, increasing revenues and, furthermore, also ensuring legal compliance for all actors involved. However, further studies are necessary to confirm and assure the results, as well as the recommendations that are derived. Further studies should examine effects of changes in material prices and reuse revenues. Moreover, other regional networks might be confronted with dissenting shares of reusable products within the collection group due to regional differences. Furthermore, regional networks vary concerning participating companies, which affects treatment costs. Hence, other regional networks should be regarded or sensitivity analyses are to be made for the described parameters.

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