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RecTecKA- Recycling of technology metals from the dismantling of nuclear facilities, taking into account radiation protection regulations

Guideline - created as part of the joint project on the BMBF's FORKA - Research for the Decommissioning of Nuclear Facilities funding concept

Darmstadt, 22/10/2024

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The project on which this report is based was funded by the Federal Ministry of Education and Research under grant number 15S9428A-D. The responsibility for the content of this publication lies with the authors.

Funded by the Baden-Württemberg Ministry of Science, Research and the Arts.

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Table of contents

1. Project objectives

In Germany as of spring 2024, all nuclear power plants (with the exception of a few research reactors) have been decommissioned and are being dismantled according to nuclear law. Components with a high potential for valuable metals and alloys were installed and used in nuclear power plants to fulfil a wide range of technical functions. Intensive discussions and activities are being conducted in Germany and the European Union with the aim of increasing the extraction of valuable materials from the anthropogenic stockpile under the buzzword "urban mining". The RecTecKA project, which is funded by the German Federal Ministry of Education and Research as part of the "FORKA - Research for the Decommissioning of Nuclear Facilities" funding programme and additionally supported by the Baden-Württemberg Ministry of Science, Research and the Arts, addresses this interface and pursues the following key project objectives:

- Create an inventory of recyclable metals and alloys indicating possible masses, contamination states and concentrations in the respective components,
- Analyse separation and recycling options as they impact recycling quality for the main valuable metals and alloys, taking into account technological and radiological boundary conditions,
- Analyse the recycling potential of the main valuable metals and alloys and their associated economic and environmental impacts, and
- Estimate and scale the potentials determined for the nuclear power plans (NPPs) scheduled for decommissioning in Germany.

To carry out the research project, the Philippsburg nuclear power plant with units 1 (KKP 1: boiling water reactor) and 2 (KKP 2: pressurised water reactor) were examined as model plants. This covered the existing reactor types. It should also be noted that the two units were built at different times. The investigations are intended to provide an approach for generalisation to other nuclear power plants.

2. Brief description of the Philippsburg nuclear power plant

The Philippsburg nuclear power plant is located approximately 30 kilometres north of Karlsruhe on an island in the Rhine river and is operated by EnBW Kernkraft GmbH (EnKK). The boiling water reactor KKP 1 was commissioned in 1980 with a gross electrical output of 926 MWe. It was decommissioned in August 2011, with the decommissioning and first dismantling licence (1st SAG) granted in April 2017; the second dismantling licence (2nd AG) was granted in July 2020. The pressurised water reactor KKP 2 was commissioned in 1985 with a gross electrical output of 1.468 MWe. Decommissioning of KKP 2 and the dismantling and decommissioning licence (SAG) took place in December 2019. The following aerial photo shows the decommissioned and partially dismantled plant (the cooling towers have already been demolished)[1].

[1] Status of the recording. September 2023, with the kind permission of EnBW Kernkraft GmbH.

Figure 2-1 **Aerial view of the Philippsburg plant complex (KKP 1 and KKP 2)**

The following diagram provides a simplified representation of the KKP 1 boiling water reactor:

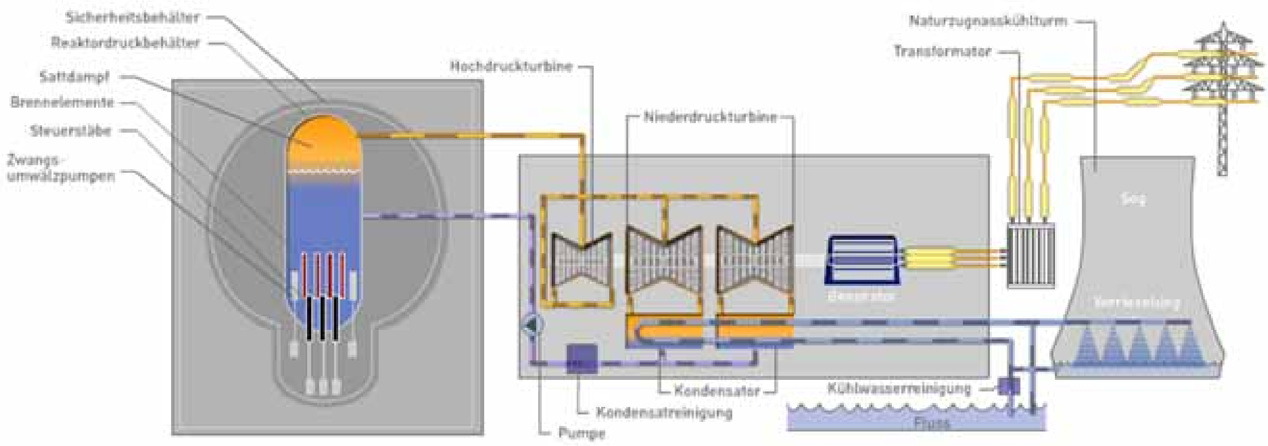


Figure 2-2 **Simplified schematic of the boiling water reactor KKP 1, source: EnBW**

The pressurised water reactor KKP 2, which has significantly larger conventional plant components due to the secondary cooling circuit, is shown in the following diagram.

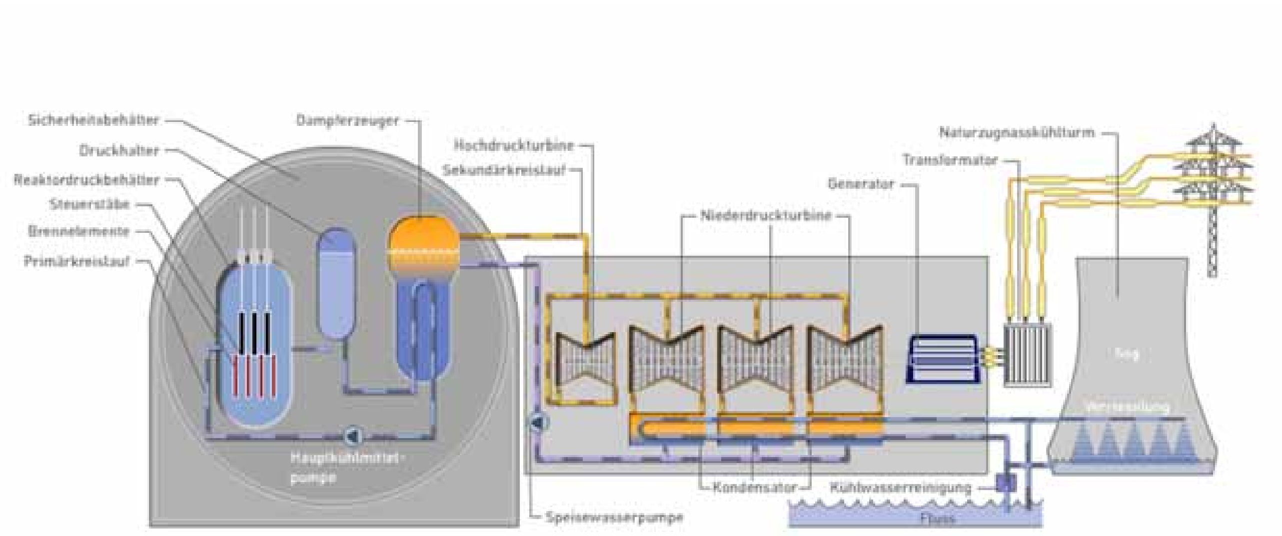


Figure 2-3 **Simplified schematic of the pressurised water reactor KKP 2, source: EnBW**

3. Brief description of the main project steps

The RecTecKA research project was organised into five work packages briefly outlined here:

- Identify system parts and components with high recycling potential, inventory of valuable metals and alloys KKP 1 and KKP 2,
- Determine the intrinsic material value,
- Consider economic and ecological aspects,
- Analyse tension between recycling potential vs. release,
- Assess the ecological and economic potential by recycling valuable metals that result from Germany's NPP decommissioning.

The work packages were completed by the partners Öko-Institut (ÖI), TU Clausthal (TUC), EnKK and Electrocycling (Elec) using the model plants KKP 1 and KKP 2.

In the course of the project, it became clear that the inventory of relevant plant parts and components and the quantification of the valuable metals and alloys contained therein were very challenging tasks. The necessary research was carried out with intensive involvement and support from various experts from EnKK at the Philippsburg site and included full-day plant inspections, interviews and the evaluation of numerous documents, many of which were only available in paper form. Regardless, the interdisciplinary co-operation laid a successful foundation for subsequent work.

4. Inventory survey

The inventory survey considered components in PPP 1 and PPP 2 that contain significant quantities of valuable base and technology metals. The target metals[2] included in particular copper, nickel, chromium, aluminium, silver, gold and the platinum group metals. Metals found in a nuclear power plant can be present in pure form (e.g. copper pipe) or in alloyed form (e.g. components made of

[2] Low-alloy steels were not the focus of the research project, as sufficient information was available from previous studies.

high-alloy steel). **The basic requirement for inventory survey is that the components can be released**. The following are analysed:

- **Large components**, such as heat exchangers, tanks or pumps. These contain large quantities of stainless steels, titanium or copper alloys.
- **Cables, electric motors (‘e-motors’) and actuators,** which contain large quantities of copper.
- **Components for electrical and control technology,** which contain large quantities of copper and precious metals.

4.1. Large components

Within the inventory survey, components were included if the corresponding large components had a high quantity of high-quality metals. A "high quantity" was defined here as the quantity in a component (per redundancy) exceeding 1 000 kg. High-value metals in the area of large components include copper, nickel, titanium, chrome and aluminium. Furthermore, components were only considered in this analysis if radioactive contamination of the components could be ruled out by release or if release appears possible to prove the further use or utilisation of the component parts as non-radioactive material.

Large components were first systematically identified by Oeko-Institut on the basis of existing plant documentation. In the case of identified large components from KKP 1 and KKP 2, the EnKK experts in a preliminary assessment based on their knowledge of the components were often able to exclude components that contained no or only small quantities of valuable metals. For large components that were expected to contain quantitatively relevant technology metals, material data sheets were requested from the operator and analysed.

Large components were systematically inventoried in order to determine the recyclable material potential. The following clusters were formed for the pressurised water reactor KKP 2:

- Reactor including safety systems,
- Auxiliary/additional systems of the primary circuit,
- Facilities in the machine house,
- Main and secondary cooling water system,
- Emergency power generation and emergency power supply system.

For KKP 2, the facilities in the engine house contribute by far the largest amount by weight of valuable metals in large components. The amounts in tonnes determined for the powerhouse are shown in the following figure.

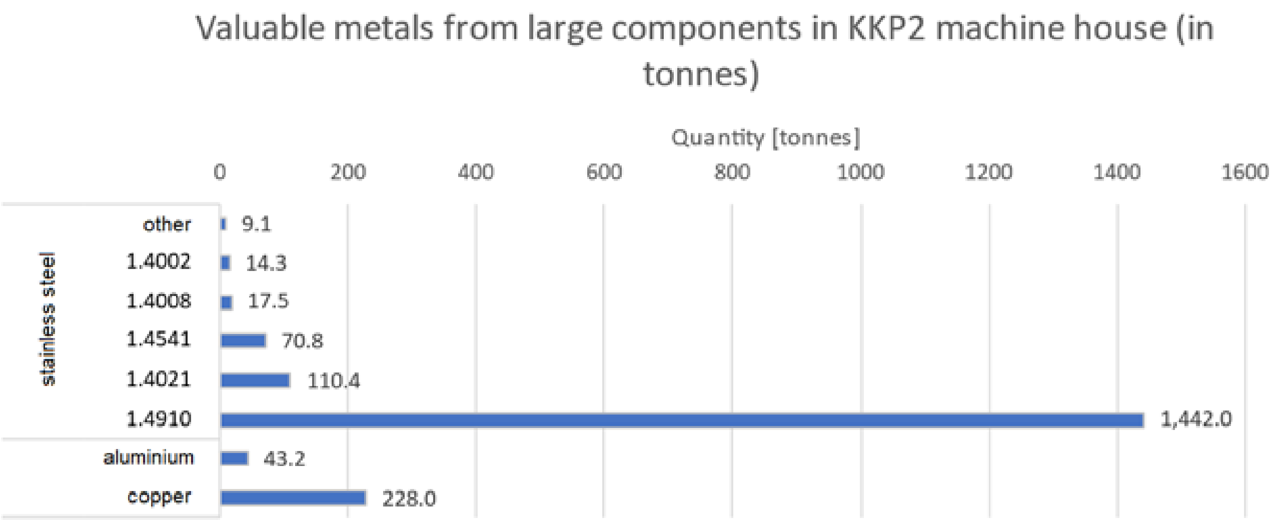


Figure 4-1 **Valuable metals from large components in KKP2 machine house (in tonnes)**

All different compositions of stainless steel account for the largest share of the value potential from metal recycling in a decommissioned NPP. In terms of quantity, stainless steel 1.4910 (DIN standard designation: X3CrNiMoN17-13) is particularly relevant with 1 442 tonnes. This contains 17 % chromium and 13 % nickel as primary alloying elements.

The number of large components in the KKP 1 boiling water reactor (compared to KKP 2) that both contain valuable metals in significant quantities and are considered contamination-free is negligible due to the design. Components that fulfil the aforementioned requirements (i.e. releasable) are the emergency feed pump, the borating tank (i.e poisoning tank), the USUS cooler (i.e independent sabotage and accident protection system), the operational H_2 recombiners, the generator, the excitation machine as well as the generator discharge and the emergency diesel generators.

The figure below summarises the amount in weight (tonnes) of valuable metals of all major components in KKP 1.

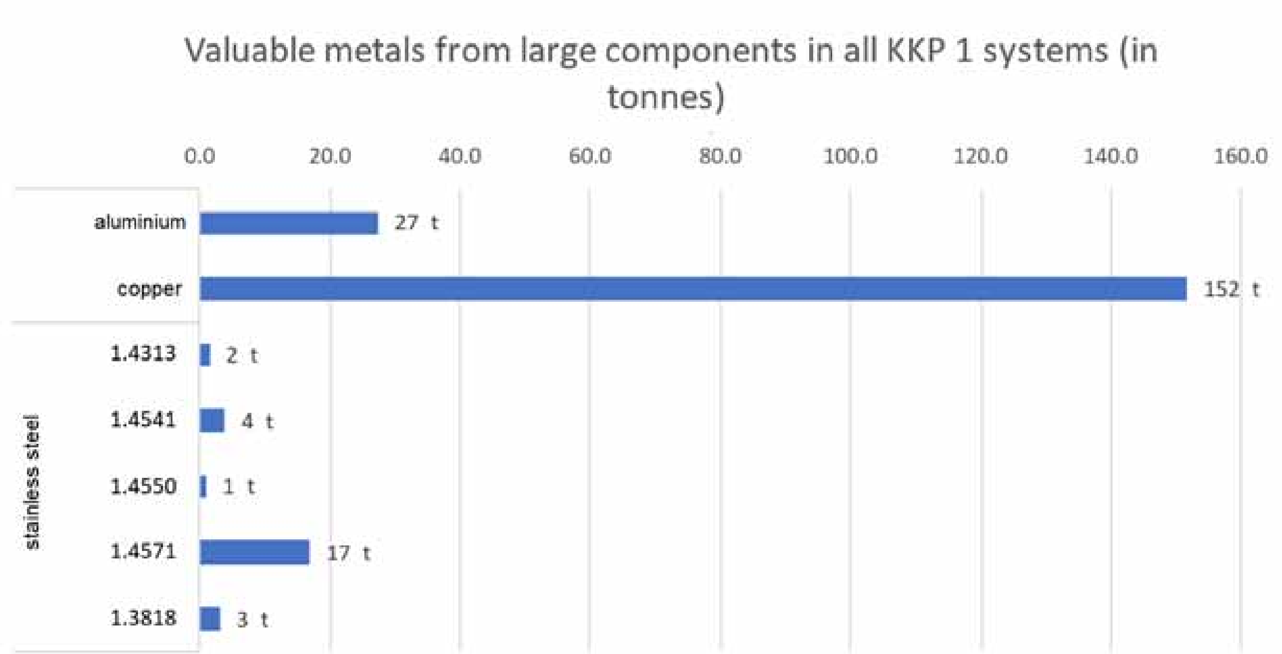


Figure 4-2 Valuable metals from large components in all KKP 1 systems (in tonnes)

4.2. Cables, electric motors and actuators

The total quantity of copper identified from cables and electric motors is almost 2000 t from KKP 2. In addition, there are 161 t of aluminium from electric motors and smaller quantities of copper (4.4 t) and aluminium (17.4 t) from numerous actuators.

For KKP 1, almost 1270 tonnes of copper was identified from cables and electric motors. In addition, a few tonnes of copper and aluminium come from actuators.

4.3. Components for electrical and control technology

The inventory results for KKP 1 and KKP 2 from control technology components, which include numerous electrical components (switches etc.), medium-voltage switches and control cabinets with circuit boards, are presented below. To survey all the components, the partners TU Clausthal and Electrocycling carried out comprehensive preparation and analysis processes aimed not least at recording the valuable precious metal inventories in as much detail as possible. The results for KKP 1 and KKP 2 are summarised in the following overview.

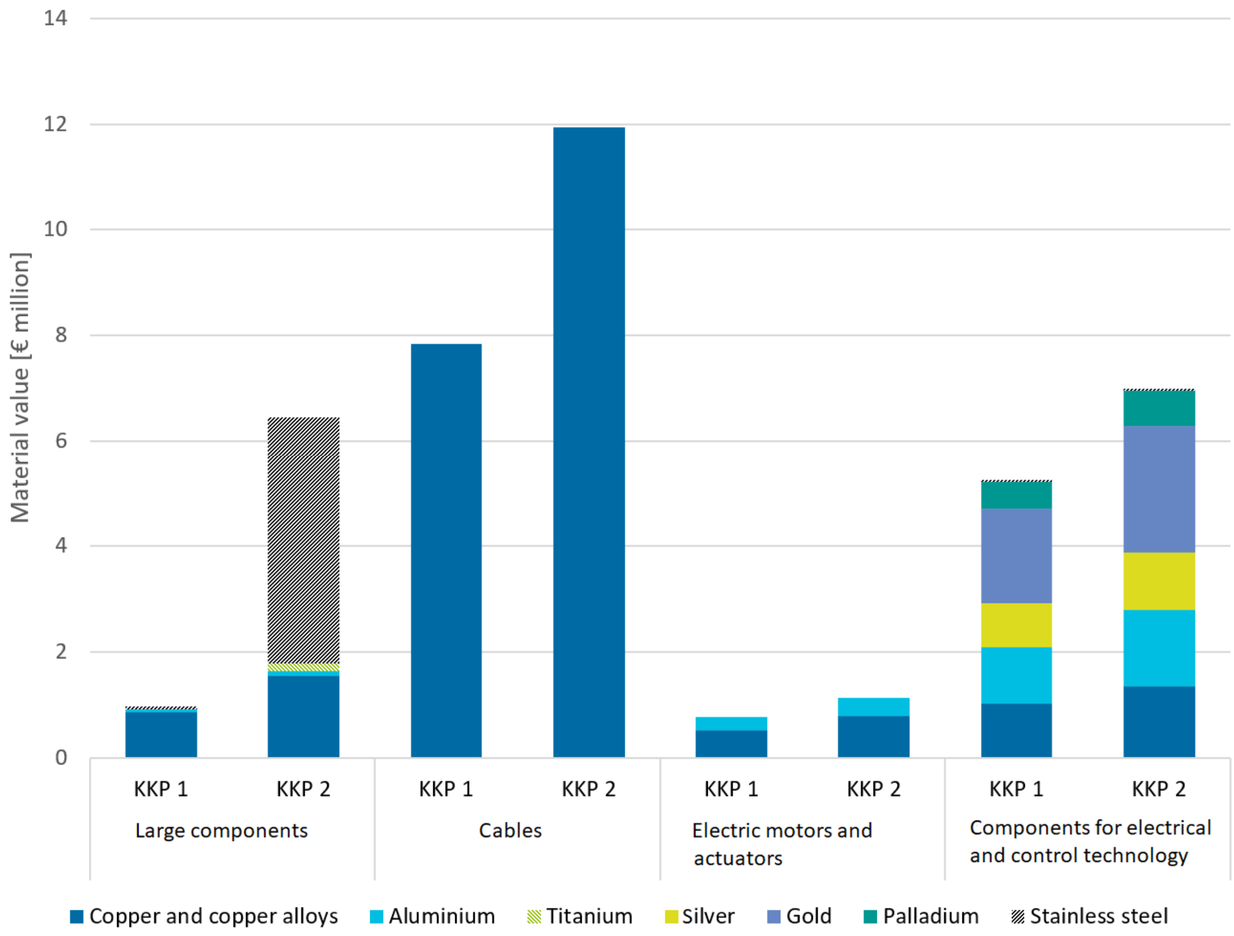
Table 4-1 Components of the electrical and control technology

Category	KKP 1	KKP 2
Selected valuable metals and alloys in tonnes		
Copper and copper alloys	190	253
Aluminium	571	761
Stainless steel	1.7	2.2
Precious metals in [kg]		
Silver	1322	1760
Gold	35.8	47.9
Palladium	8.94	12.0

5. Material values of the components

In the following figure, the monetary material values of all valuable components identified in KKP 1 and KKP 2 are summarised separately for large components, cables, motors and actuators and electrical and I&C components with their respective cumulative material values. Low-alloy steels and their material values are not categorised as recoverable metals and are therefore not presented.

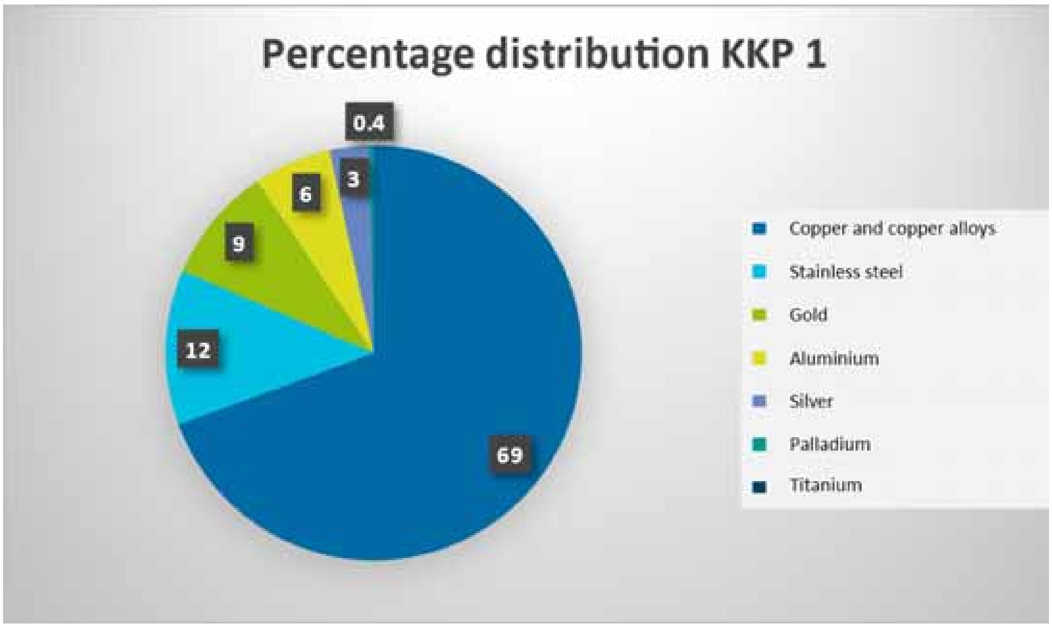
Figure 5-1 Material values of the identified components



Source: RecTecKA-Network

For KKP 1, this results in a total material value of approximately €15 million, distributed over the various metals as indicated in the figure below.

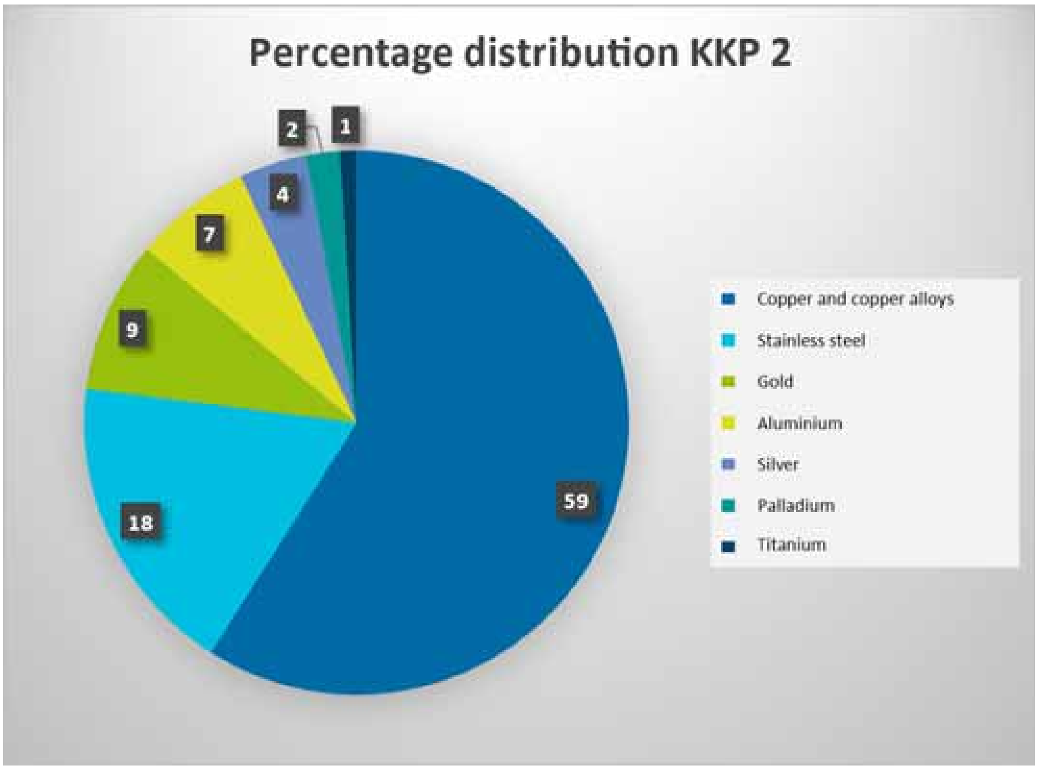
Figure 5-2: KKP 1: Value share from different metal component compositions (in %)



Source: RecTecKA-Network

For KKP 2, the total material value is approximately €27 million, distributed as a percentage over the various metals as indicated in the figure below.

Figure 5-3: KKP 2: Value share from different metal component compositions (in %)



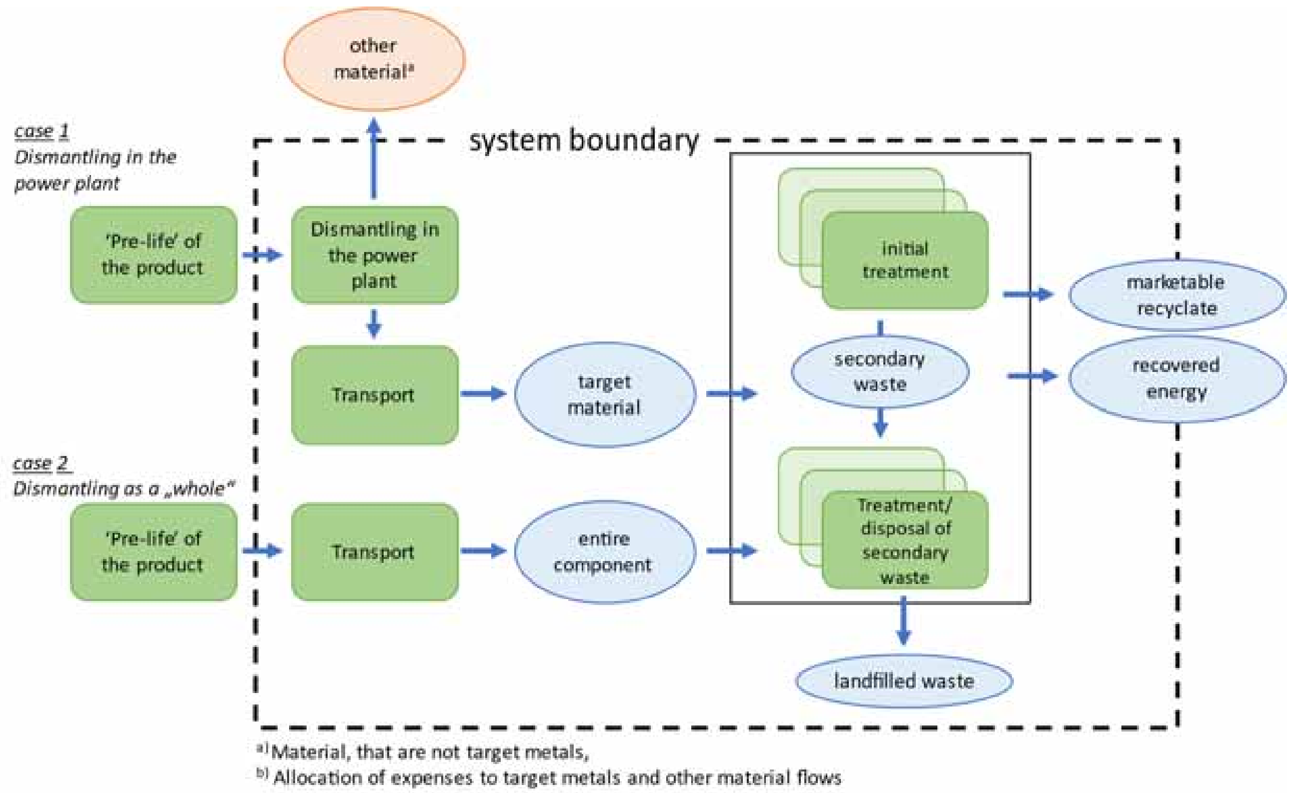
Source: RecTecKA-Network

The significantly higher material values in KKP 2 compared to KKP 1 result from the higher quantity of components that can be fed directly into further utilisation as part of the handover process or that can be released. For large components in particular, this leads to a significantly higher quantity of stainless steels that can be recycled. Furthermore, the larger dimensions of KKP 2 in contrast to KKP 1 mean that larger quantities of cables, motors, actuators and electronic components are also available. However, there are also always differences due to the reactor design type. It should therefore be noted that, even within boiling or pressurised water reactors, different materials and material quantities must be inventoried in detail depending on the series and year of construction.

6. Life cycle assessment

As part of the RecTecKA joint project, Oeko-Institut carried out a comprehensive **life cycle assessment** in accordance with ISO 14040/14044 for the valuable metals identified in KKP 1 and KKP 2 with the aim to quantify the environmental benefits of professional processing and recycling methods. For the life cycle assessment, it was assumed that the respective components are either dismantled and separated in the plant itself (primarily large components) or removed from the NPP in their entirety (cables and motors as well as components of the electrical and control technology). In the latter case, the recycling path for the entire component occurs outside the nuclear power plant. The following figure shows the system boundary schematically.

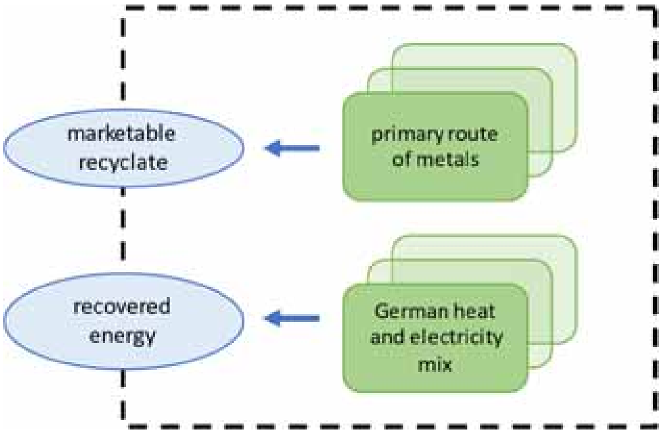
Figure 6-1 Schematic representation of the system boundaries



Source: RecTecKA-Network

Credit is given for recovered recyclates and energy in accordance with the substitution method. For energy, the credit is allocated according to the German electricity and heat mix. For recovered metals, the loads of the primary route are credited first.

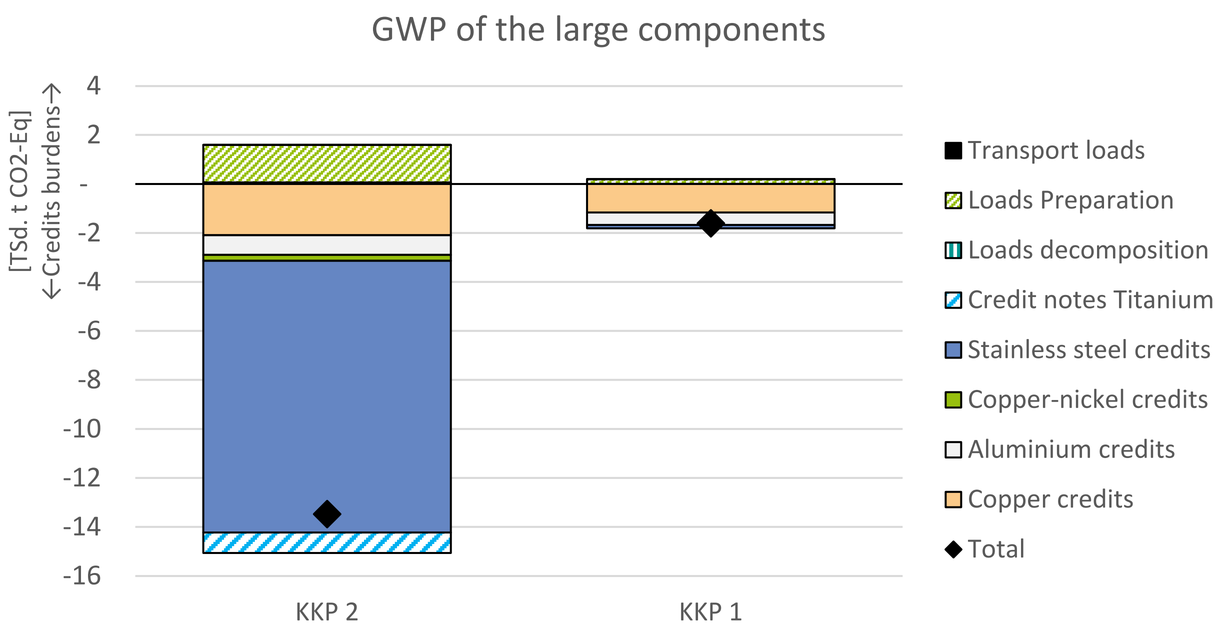
Figure 6-2 Substitution of recyclates and recovered energy



Source: RecTecKA-Network

Significantly fewer components suitable for recycling were identified for KKP 1, as the majority of the components were radioactive. As shown in the following figure, a total potential net credit in GWP (global warming potential) of -13.48 thousand tonnes of CO_2-eq was determined for the large components in KKP 2. For the large components from KKP 1, this value is only -1.52 thousand tonnes CO_2-eq. The net credits from KKP 1 are largely due to avoided copper production.

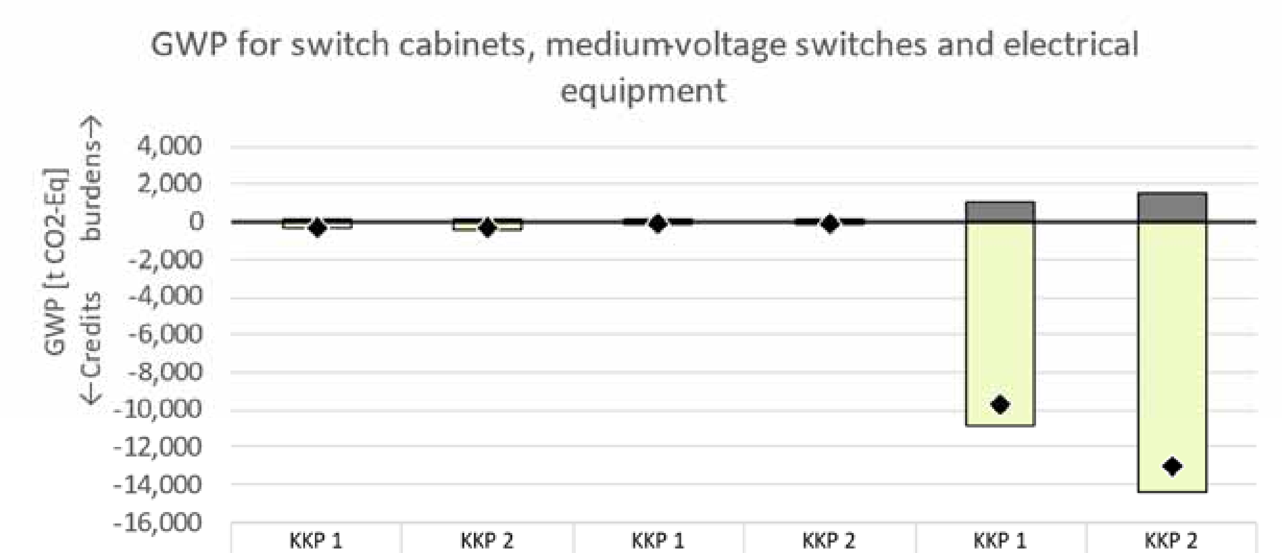
Figure 6-3 GWP Major components for PPP 2 and PPP 1 in thousand tonnes of CO_2-eq



Source: RecTecKA-Network

The next figure summarises the results for the recycling of switch cabinets, medium-voltage switches and electrical equipment. For KKP 1, the net credits are around -10 thousand tonnes of CO_2-eq and for KKP 2 about -13.5 thousand tonnes of CO_2-eq.

Figure 6-4 GWP for switch cabinets, medium-voltage switches and electrical equipment in relation to the total tonnages in KKP 1 and KKP 2



	switch cabinets KKP 1	switch cabinets KKP 2	medium voltage switches KKP 1	medium voltage switches KKP 2	electrical equipment KKP 1	electrical equipment KKP 2
Credit	-310	-403	-64	-53	-10845	-14459
Burdens	36	45	14	12	1112	1483
Total	-275	-358	-49	-41	-9733	-12976

Source: RecTecKA-Network

Overall, recycling of the identified valuable materials has a credit potential (net) of at least 22 thousand tonnes of CO_2-eq for KKP 1 and around 43 thousand tonnes of CO_2-eq for KKP 2. For the other environmental impact categories examined in the LCA (such as emissions of acid images), the results are also clearly positive for the recycling of valuable materials.

7. Obstacles with regard to release

The RecTecKA research project also identified **general obstacles to metal recycling** that can be traced back to clearance. As part of a clearance procedure, objects or materials are tested for radiological contamination and, if necessary, decontaminated before they can be conventionally reused or disposed of. Depending on the composition and previous use of the material or object, this test can be time-consuming because radiological characterisation and expert assessment are required. Therefore, optimisations in the release process were also investigated.

The following **obstacles to approval** were identified:

- During dismantling planning, it is not always immediately known which materials were used in the individual system components. Details on this must be prepared in advance specifically for recycling.
- When decommissioning nuclear facilities, there are many factors that influence the timing of the final disposal of the materials. Preparatory work for recycling can affect the time to final disposal.

Significant operating costs are incurred for each month a facility is in the process of being dismantled. The economic benefits of recycling can be cancelled out by extended dismantling times.

- Preliminary examinations for radiological characterisation can be very time-consuming.
- Decontamination with the upstream dismantling of complex plant components as well as the disposal of radioactive secondary waste from decontamination can be associated with additional technological, time and financial expenditure and must be taken into account as part of the dismantling planning.
- Complex plant components can mean additional work during the free-measurement process. The effort involved in dismantling must be weighed against the potential benefits from recycling.
- Recycling requires storage space, which is in short supply in nuclear decommissioning. Creating additional interim storage options can involve considerable expense.
- For the specific release of "scrap metal for recycling", the search for a suitable smelting plant that is prepared to accept the released metals may be difficult.
- The decontamination and approval process is time-consuming and prolongs the dismantling process.
- A public attitude of rejection can lead to restrictions on the possibilities for recycling metals from nuclear decommissioning.

Possible optimisations[3] in the approval process with regard to valuable materials can be:

- Having a good understanding of the initial condition of a nuclear facility after final shutdown is crucial. The characterisation of the plant components with regard to recycling should be carried out at an early stage.
- Systematic information for metal recycling should be compiled so that it can be incorporated into dismantling planning. As far as possible, dismantling planning should take into account metal prices and their development.
- An efficient and timely public discourse on dismantling, clearance and metal recycling helps to build trust.
- Costs for the disposal of radioactive waste can be avoided through a higher clearance rate. However, the costs of decontaminating components must be proportionate.
- Planning sufficient storage and logistics space has a positive effect on the necessary dismantling activities such as dismantling, decontamination and release. Additional storage areas should be planned for as early as the dismantling planning stage.

In connection with the optimisation of release processes, the **steam generator** offers as an example of a complex plant component that has not yet been recycled or has only been partially recycled but is interesting for metal recycling due to its material composition.

In pressurised water reactors, heat is transferred from the primary to the secondary circuit in the steam generators. Steam generators consist of a dome-shaped steam dome, four rings, the tube plate and the dome-shaped water chamber. Many thin heating pipes run through the tube plate. As

[3] Optimisation means returning more valuable materials to the circular economy. Release procedures and release limits and the underlying radiation protection requirements are not called into question.

the steam generator is connected to both the contaminated reactor cooling circuit (primary circuit) and the uncontaminated secondary circuit, and it has a very large surface area due to the heating tubes, decontamination of the part connected to the primary circuit would be particularly time-consuming. The weight of a steam generator is approximately 150 to 450 tonnes, depending on the type of system. Recycling the secondary side is relatively simple and is already practised: the thick-walled cylinder can be mechanically dismantled and, if necessary, simply decontaminated. The following examples are based on steam generators used in EnKK plants. Of particular interest for recycling are:

- the heating tubes of the steam generator, made of stainless steel (X2NiCrAlTi32-20, 1% Mn, 21.5% Cr, 33.5% Ni). This involves approx. 4 000 heating tubes with a total weight of 13.5 tonnes. The metal value of X2NiCrAlTi32-20 is €4 320/t (as of 2024). This means that the total value of the heating tubes is approx. 58 320 € per steam generator or approx. 233 300 € for all four steam generators in KKP 2.

- the tube sheet made of Inconel 600 (nickel-based alloy with 1 % Mn, 15.5 % Cr, 72 % Ni), approx. 620 mm thick, diameter 3 m, weight unknown The tube sheet consists of a large, perforated plate into which the heating tubes lead. Due to its geometry, the perforated plate is difficult to decontaminate. So far, it is planned that it will be disposed of in a landfill.

Entsorgungswerk für Nuklearanlagen GmbH (EWN) has developed a method (chemical process) to specifically release the heating pipes as "metal scrap for recycling", i.e. for melting down. Processes based on high-pressure water jetting have also been tested for the heating pipes and initial practical trials have been successfully carried out at a German company. In 2007, the steam generators from the Stade NPP were transported to Sweden for harmless recycling, where they were dismantled and melted down. The steam generators in Mülheim-Kärlich[4] were dismantled using special saws. The dismantled casings could be measured and fed into the conventional recycling cycle. The heating tubes are destined for the final storage facility at Schacht Konrad. Large components such as steam generators can be stored temporarily in EWN's northern interim storage facility in Greifswald for decay storage. This decouples the dismantling work and the subsequent dismantling of larger plant components, which can help to speed up the dismantling process. Decontamination and subsequent release may then be easier. However, decay storage facilities are not available at every site.

A large acid bath would be required to decontaminate the dismantled primary side parts of the steam generator (approx. 5 tonnes). A suitable chemical would have to be developed for this. The acid not only attacks the contaminated oxide layer, but also the surface of the plated stainless steel metal parts. If the plating were to be dissolved in the acid, a process might have to be developed to recover the metal from the acid. As such, a large bath is not currently available at any nuclear power plant site in Germany. Therefore, the following would have to be developed :

- A centralised facility should be created in which large metal parts can be decontaminated in a controlled area.

- A specific bath chemistry must be developed for each individual plant, as the radiology of the individual nuclear power plants is different.

- steam generators and other large components would need to be transported there.

[4] It should be noted that the Mühlheim-Kärlich NPP was only in operation for a very short time and therefore the contamination of the steam generators and the steam generator heating pipes was lower.

- the acid would need to be cleaned of radionuclides after decontamination.
- logistics would need to be set up to enable the plant components to be allocated to the corresponding nuclear power plants, as the radionuclides would have to be returned to the corresponding nuclear power plant as radioactive waste.
- The economic viability of the realisation should be examined in a feasibility study.

It is not possible to judge here how much effort would be involved in developing a process as described above and whether such a process would result in all essential primary-side parts of the steam generator being releasable; this would require further investigations. It would also be necessary to examine how such a process would be assessed in terms of its life cycle assessment.

8. Conclusions and outlook

The following conclusions can be drawn from the extensive results of the RecTecKA joint project:

- The results of the analyses at the KKP 1 and KKP 2 plants clearly show a high recycling potential for valuable metals and alloys, which can be returned to the material cycle without any problems. In terms of quantity, copper and copper alloys, aluminium and stainless steels dominate the metals/alloys suitable for recycling. Precious metals (gold, silver, palladium) from various electronic components in KKP 1 and KKP 2 also have a high economic value potential from recycling. This potential is already being largely utilised based on the requirements of radiation protection legislation and the Closed Substance Cycle Waste Management Act.
- The work of the collaborative partners also shows that the identified metal inventories that are available for high-quality recycling can predominantly be utilised through simple and conventional dismantling processes such as mechanical separation of stainless steels from low-alloy steels in large components, conventional processing of copper cable scrap and electric motors and simple processing and refining of circuit boards and other electronic scrap. This means that the high value potential from these components can be realised comparatively easily and with little effort as part of the dismantling of nuclear power plants and that this is already being exploited in dismantling practice. This conclusion explicitly excludes radioactively contaminated or even activated parts and components with regard to the low effort mentioned above.
- The identified recovery potential for valuable metals and alloys is significantly higher in the case of the pressurised water reactor KKP 2 compared to the boiling water reactor KKP 1 due to the design. Although KKP 2 has a higher net power than KKP 1, the more decisive factor for the differences is that, in the case of a boiling water reactor, considerably more plant components (especially in the turbine building) are radioactively contaminated via the primary circuit than in a pressurised water reactor and decontamination processes can therefore be more complex.
- Overall, scaling up the results for KKP 1 and KKP 2 to all relevant (commercial) reactors in Germany results in a material value for valuable metals and alloys of several hundred million euros. For all pressurised and boiling water reactors in Europe, a material value in between 1 and 10 billion euro is calculated.
- Based on the results of the comprehensive life cycle assessment of the RecTecKA project for KKP 1 and KKP 2 and their upscaling to all nuclear reactors in Germany as a whole, high-quality recycling of the metal inventories could result in greenhouse gas savings of almost 850 000 tonnes of CO_2-eq. This corresponds to the annual emissions of around 90 000 German inhabitants. For

Europe as a whole, the savings potential would be 5.35 million tonnes of CO_2-eq, which is roughly equivalent to the CO_2-eq emissions of 750 000 Europeans per year.

- Selected examples of radioactively contaminated components, such as steam generators, which were analysed in more detail in the RecTecKA project, clearly show that there is further potential for metal recycling in individual cases. However, considerable personnel and other resources must be provided or factored in for the design and implementation of the decontamination processes as well as for the necessary release procedures.
- However, the above-mentioned expenses for decontamination and clearance are offset by considerable savings of €30,000/m^3 with an upward trend from avoiding final disposal costs for radioactive waste. It is clear that the decision-making process (decontamination and clearance versus final disposal as radioactive waste) requires comprehensive case-by-case analyses.

The following points can be emphasised as an **outlook** from the results of the RecTecKA joint project:

- The dismantling of nuclear power plants in Germany offers an attractive and significant source of secondary raw materials, including copper, aluminium and stainless steels, but also precious metals such as gold, silver and palladium.
- Tapping the potential for the aforementioned valuable metals and alloys from dismantling nuclear power plants is directly in line with the objectives of the European Critical Raw Materials Act (CRMA)[5] , which came into force in April 2024 and is therefore a highly topical and strategic field for Germany and the EU.
- The experts from the joint venture partner EnKK have also explicitly pointed out that many findings from the conventional plant areas of nuclear power plants that relate to metal inventories of parts required in all thermal power plants (e.g. generators) could also be applied to dismantling coal and natural gas power plants. Over the next few years, the potential for metal recycling in the large number of decommissioned and still to be decommissioned coal-fired and natural gas-fired power plants must be analysed in more detail using inventory surveys similar to those in RecTecKA.
- Considerable research and development efforts will be required for a possible expansion of the release of components from NPP. Further potential for particularly relevant individual components, such as steam generators, still needs to be tapped. As already described, these activities will involve considerable expenditure and must be researched and tested. However, if successful, these activities promise positive economic results by reducing waste volumes and hence the considerable and increasing final disposal costs. It is therefore definitely worth investing further effort here in the coming years.

5 Regulation (EU) 2024/1252