# ROSE-Trans – The Role of Secondary Resources in the Austrian Energy Transition

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**Austrian Institute of Economic Research – WIFO, University of Natural Resources and Applied Life Sciences, Vienna – ABF-BOKU**

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A concerted worldwide effort to reach the goals of the Paris Agreement, i.e., climate stabilisation to well below +2°C above pre-industrial levels, and decarbonisation until mid-century, brings about a substantial increase in raw material demand for clean energy technologies. Yet, energy transition raw materials show high emission intensities in production. Producing secondary resources, in particular metals, from recycling End-of-Life (EoL) waste streams of photovoltaics, e-vehicles, and wind (PEW) requires substantially less energy input than converting it from ore. Recovering resources from waste streams through recycling therefore relieves pressure i.a. in primary resource supply, and climate mitigation. Despite a growing stock of literature on the beneficial effects of circular material principles such as recycling, the evidence base for its economic potentials at system level (i.e., for nation states) remains vague. The aim of the study is firstly, to quantify the potential of EoL waste streams of PEW, including the strategic raw materials for recycling resulting from decarbonizing the Austrian economy, and secondly, to assess the economic impacts from potential recycling loops of PEW using the macroeconomic model WIFO.DYNK. Results show that from an investor's point of view, recycling plants appear not to be profitable under different price assumptions. Introducing a minimum "gate-fee" for EoL waste streams can yet trigger the profitability and ensure relevant investments for recycling are made. From a macroeconomic point of view, it brings about value-added and employment creation, and additional dividends in the spheres of climate mitigation and resource security.

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## Contents

## List of Figures

## List of Tables

### Annex

## List of Abbreviations

| | |
|---|---|
| AC | Alternating current |
| BMS | Battery Management System |
| BOS | Balance of system |
| CdTe | Cadmium telluride |
| CFRP | Carbon fibre reinforced polymer |
| c-Si | Crystalline silicon |
| DC | Direct current |
| EoL | End-of-Life |
| EV | Electric vehicle |
| GFRP | Glass fiber reinforced polymer |
| IEA PVPS | International Energy Agency Photovoltaic Power Systems Programme |
| PCB | Printed circuit board |
| PEW | Photovoltaic/Electric-Vehicle/Wind Power Plants |
| PV | Photovoltaic |
| WEEE | Waste electrical and electronic equipment |
| WPP | Wind Power Plant |

# 1. Introduction

The transition to clean and renewable energy brings about a substantial increase in the demand for raw materials, in particular metals. On a global scale, a concerted effort to reach the goal of the Paris Agreement, to stabilize the climate at a temperature rise of well below +2°C above the pre-industrial level, would mean a quadrupling of mineral requirements for clean energy technologies by 2040 (IEA 2021). Solar photovoltaic (PV) plants, wind farms, electric vehicles (EVs) and battery storage systems generally require more raw materials to build than their fossil fuel-based counterparts. A typical electric car, for instance, requires six times the mineral inputs of a conventional car and an onshore wind plant requires nine times more mineral resources than a gas-fired plant (IEA 2021). The transformation of the energy system is thus accompanied by a change in the demand for raw materials – from fossil resources to metals.

Main raw materials used in renewable energy systems are copper, cobalt, nickel, lithium, graphite, aluminum, steel, and rare earth elements such as dysprosium, neodymium, and praseodymium. These resources are mostly imported and recycling rates of some metals such as rare earth elements or lithium are very low. A reliable supply of the raw materials required is therefore an essential prerequisite for the successful implementation of the energy transition. Climate mitigation is thus associated with issues of energy and resource security, as different international bodies disclose (IEA 2021, World Bank 2020, European Commission 2020c).

Some examples of supply security concerns expressed for individual raw materials are summarized below (e.g. Nakano 2021).

- For lithium, which is used in lithium-ion batteries (LIB) to power electric vehicles and to store energy, generated from volatile sources such as PV and wind, there is less supply concern in the near future, but in the medium-term, large investments are needed to avoid a significant market shortcoming beyond 2025. Yet, there are only five countries producing lithium, and China accounts for roughly 60% of global lithium refining capacity (Nakano 2021). Bottlenecks for the EU are in the raw materials stages and the Li-ion cells production. Currently, the EU provides less than 1% of LIB (European Commission 2020c).
- For cobalt, the concentration of supply in the Democratic Republic of the Congo will continuously remain a concern due to the country's large share in global extraction (European Commission 2020c).
- For natural graphite, China is dominant in spherical graphite production, but when prices become high, synthetic graphite can become a substitute (European Commission 2020c).
- For rare earth elements, China holds a dominant market position driving the relevant value chains extremely vulnerable (Nakano 2021).

Growing competition over critical raw material supply and clean energy manufacturing, instability in the global supply chains and rising global competition, i.e. from China, have triggered a rethinking with respect to the resilience of global supply chains, and updated national und supranational strategies on how to cope with supply risks of strategic materials (Nakano 2021, European Commission 2020c). A recent case of supply chain risks was conveyed by the unforeseen event of the COVID-19 pandemic in early 2020, which obstructed global supply chains and put strains on the manufacturing sector (Klien et al. 2021). China's grown central role and importance to global trade in renewable energy technologies, e.g. as a primary producer of high value battery cells or solar panels, and its potential impact on key global value chains, became food for thought to many actors in the field (see e.g. Deloitte 2020).

Greenhouse gas (GHG) emissions from primary resource extraction and processing for renewable energy systems present another challenge for climate mitigation. Energy transition minerals have relatively high emission intensities (IEA 2021). Mining and refining of metals are responsible for about 8% of the total global primary energy consumption and associated GHG emissions, including many local environmental and health problems from water abstraction to the release of toxic substances (IRP 2015). High grade metal ores are becoming increasingly scarce and require ever-larger amounts of energy and water to extract and process them.

Producing secondary resources, in particular metals, from recycling often requires less than half as much energy and therefore carbon emissions as converting it from ore. By recovering resources from waste streams, recycling relieves pressure in primary resource supply. For bulk metals, such as steel and aluminum, recycling technologies are well established, however, this is not yet the case for many energy transition metals such as lithium and rare earth elements (IEA 2021).

In the context of climate mitigation and resource security, the circular economy has evolved as an economic paradigm with proclaimed benefits for local employment, value creation and the environment and particularly the climate (OECD 2020, Ellen MacArthur Foundation and Material Economics 2019, Material Economics 2018). The circular economy aims at increasing material efficiency by ensuring resources are used in loops, i.e. re-integrated into the value chain, instead of being discarded, e.g. thermally combusted or landfilled at their end-of-life. This includes product lifetime extensions through eco-design standards, product loops driven by repair or refurbishment and recycling of materials from end-of-life (EoL) products. In case a defect device is repaired instead of being replaced with a new one, mining activities are saved in the ratio of its lifetime extension as well as many manufacturing steps, associated energy use and ultimately GHG emissions.

The transformation to a circular economy has thus become a strategic component of political agendas, both at the European level and at the national level, i.e. it is adopted in the latest National and Energy Climate Plan (NEKP; BMNT, BMF and BMVIT 2019) as well as in the "Ref-NEKP", an alternative plan developed by the Austrian climate research community. The latter refers to the circular economy as one of nine key framework measures to combat climate change (Kirchengast et al. 2019). Furthermore, the decision towards a more circular economy has entered the industrial strategy of the European Union (European Commission 2020d). The twin transitions (ecological and digital) will affect our economy, industry and society and the shift away from a linear economy is seen essential.

Despite a growing stock of international literature on the multiple beneficial effects of circular economy principles and policies, the evidence base for its decarbonization and economic potentials at system level (i.e. for nation states) remains somewhat vague. While in principle it appears plausible that enhanced circularity will reduce GHG emissions and spur economic performance through structural change from material-intensive to more labour-intensive activities, its actual potential for achieving these goals remains unclear, and demands in-depth analysis and research.

## 2. Objective of the Study

The study interlinks the shift to a climate-neutral Austrian economy including the respective deployment of renewable energy technologies with their end-of-life (EoL) material flows and develops a circularity concept for its EoL use. Different scenarios addressing recycling for EoL PV, wind and lithium-ion batteries (LIB) from e-mobility are developed and analyzed in economic terms using the macroeconomic model WIFO.DYNK of the Austrian economy. Central research objectives are

1. to quantify the potential of EoL waste streams of PV modules, e-vehicles and their batteries, as well as wind power plants (thereafter referred to as PEW), including the strategic materials for recycling, and
2. to assess the macroeconomic impacts from potential recycling loops of PEW to the Austrian economy until 2040.

For the quantification of EoL PEW volumes, and the economic impact assessment of recycling scenarios in Austria, the Transition scenario (TRANS) is used as a reference (Meyer et al. 2020, Meyer et al. 2018a, UBA 2017). TRANS describes a possible development of the Austrian economy towards climate neutrality, i.e. a reduction of energy-related GHG emissions by at least 80-95% (2050/1990), considering energy-based emissions. This includes a comprehensive set of policy measures to spur the transition, including investments into renewable energy and resource efficiency, regulatory as well as pricing mechanisms. TRANS serves as a reference scenario in terms of context and with respect to the amount of EoL PEW calculated.

Two recycling scenarios (ROSE) are developed, which focus on collection, transport and recycling schemes for EoL PEW, including the basic (ROSE_Base) and optimized (ROSE_High) economic exploitation of secondary resources from recycling of PEW devices.

In a first step to the macroeconomic assessment of the Austrian climate-resource nexus, a data set containing the potentially recyclable materials in PV plants, e-vehicles and wind power plants (PEW) installed are developed (**section 4.1, 4.2**). Material intensity and material composition are assessed for identified indicator products focusing on metals, minerals but also critical raw materials by making use of external and internal product data bases and literature. Data on material compositions are mainly based on Life Cycle Assessment (LCA) studies. The current and prospective recycling situation is determined by an in-depth literature review and interviews with experts in this field. Two variants are examined: Base Case Recycling, representing the current recycling technology, and High Efficiency Recycling, referring to more efficient recycling technologies, which are, however, not realized today due to economic constraints.

The second step is to build comprehensive recycling scenarios ROSE (Base/High) to determine the potential EoL material flows available for recycling (**chapter 5**). Considering the high growth rates of PEW in the upcoming decades according to TRANS, the waste volumes will increase substantially, and recycling routes will eventually become economically viable – depending on the prices for secondary resources – or be triggered by regulatory frameworks. Based on the literature and current Austrian practice, it is assumed that EoL PV modules and EoL batteries from e-vehicles will be recycled and recycling plants be installed in Austria. For wind plants, in contrast, foreign re-use is assumed, given the current practice of exporting wind plants at the end of their economic use phase (in first life) to foreign countries.

In a third step, the ROSE (Base/High) scenarios are assessed in a macroeconomic framework. This encompasses the selection of price bands (upper, lower, and middle) for recycled secondary resources. Dealing with new installations for the recycling of EoL batteries and PV plants, respective investment costs and current operating costs are derived from literature review and expert interviews (**chapter 9**). Modelling results are displayed, and macroeconomic impacts are discussed in the context of boundary conditions such as market price developments and policy tools for secondary resources. The subsequent section sets the scene for the climate, resource, and economic nexus.

## 3. Setting the Scene: The Climate, Resource, and Economic Nexus

On a planet with finite material resources, the circular economy is a necessity to maintain, sustain and improve well-being and material efficiency. The current economic system has grown to become "linear" and wasteful of resources, thus, leading to serious environmental impacts, among these climate change caused by the ubiquitous combustion of fossil fuels and related emissions of greenhouse gases (IPCC 2014). Fossil energy still provides the majority of essential commodities and services: heat to warm buildings, energy to transport goods and people, electricity to power appliances, and power to dig, extract, melt, refine, and transform raw materials into the manufactured products for socio-economic well-being.

Recycling is recognized as an essential strategy to reduce GHG emissions from primary resource extraction, and to enhance resource efficiency by closing resource loops so that large volumes of finite resources such as metals and minerals will be captured after use and remanufactured and thus circled instead of being discarded and lost for economic value chains. Yet, recycling is not sufficient to reach the full potential of a circular economy. Re-use and lifetime extensions are additional key strategies towards a less energy-, material- and GHG-intensive production and consumption (Ellen MacArthur Foundation 2013a, 2013b; Deloitte 2016). The circular economy is hence commonly about "reducing, reusing and recycling" (Stahel 2016).

Besides the environmental benefits expected from circular economy approaches, potential employment benefits are often mentioned on grounds of the anticipated structural changes from material-intensive to more labour-intensive economic activities. A recent paper by the OECD (2020) ascertains that a growing body of studies evolves using quantitative models to assess the employment effects from circular economy policies. Most of these studies are primarily based on material taxes as an instrument to reduce primary resource use and enhance resource efficiency. The assessed literature indicates that the transition is likely to lead to a slight net improvement in employment rates. Results yet depend on stylized policy designs, geographical coverage and revenue recycling policies. The transition to a circular economy is likely to boost economic activity in more labour-intensive sectors such as those dealing with product life extension (e.g. repairing, re-use) or in the domain of recycling, while job destructions are expected to take place in more material-intensive sectors. The OECD (2020) reviewed 47 scenarios from 15 economic modelling studies providing an overview of the current stand of existing literature in this field. The modelling studies reviewed suggest that employment gains range between 0 and 2%, with one study predicting employment gains up to 7%. Only three scenarios find a slightly negative employment outcome. Yet, employment implications vary widely across sectors and regions. The labour impacts described are likely to be asymmetric within and across countries. The specialization and sectoral structure of local economies play an important role in determining employment impacts. The lack of a comprehensive and common definition of the circular economy and the multitude of indicators and assumptions used by different studies limit the comparison of modelling results, according to OECD (2020). The assessed employment effects should thus be reflected in the context of an emerging but still limited literature on the topic. The scenario design in most modelling studies is still rather stylized and mainly dealing with material taxes. Only a few studies have yet addressed the emergence of new business models and socio-technological trends (digitalization, automation). Future macroeconomic modelling studies, they conclude, could explore additional circularity dimensions in their scenarios.

Research on integrated energy and resource analyses with respect to decarbonization and resource efficiency is also at an early stage and, consequently, great need for assessments in integrated analysis of GHG neutrality and resource conservation exists. To the authors' knowledge, there are only a few studies which take the analytical perspective of a resource-efficient transition to a low-carbon economy, namely the World Energy Outlook 2019 (IEA 2019), which comprises material efficiency strategies in its decarbonization scenarios, or the study by the German Federal Environment Agency, which accounts for the raw material and resource demand with respect to reducing GHG emissions (FEA 2017). Yet, these scenario analyses miss the link to a comprehensive economic impact assessments of material efficiency strategies in decarbonization and renewable energy deployment.

Analyses that combine material flows and macroeconomic input-output frameworks are, however, widely applied (Bruckner et al. 2012, European Commission 2014, Giljum et al. 2017, Bösch et al. 2015, Liang et al. 2017, Wiedmann et al. 2015), yet macroeconomic impacts that consider recycling technologies explicitly are generally scarce (Haas et al. 2015). An explorative study for Austria assessed the macroeconomic impacts of recycling for well established (recycling) product groups such as steel, aluminum, paper und glass, and came to the conclusion that recycling generates about 0.5% of the Austrian GDP and 0.4% of the Austrian employees in 2014 while saving about 8 $MtCO_{2e}$ including international value chains (Meyer et al. 2018b). Even though a pioneering paper by Di Vita (1997) highlighted the importance of considering macroeconomic implications of recycling more than two decades ago, there is currently only a handful of macroeconomic models that explicitly consider recycling technologies, which mainly focus on the Japanese economy, where waste management has a high priority due to lack of landfills (Nakamura and Kondo 2002; Masui et al. 2000).

The present study aims to address this research gap by providing an integrated analysis of the economic potential of material efficiency strategies in the decarbonization of the Austrian economy, addressing the climate-resource-economic nexus as a national case study.

## 4. Methodology and Data

### 4.1 Material Flow Analysis (MFA)

The aim of this section is to determine the secondary resource potential for recovery from the current inventory of photovoltaic plants, wind turbines and electric vehicles. To determine the resources used within the systems, a material flow analysis (MFA) is carried out. According to ÖNORM S 2096/2005, MFA deals with the "identification and quantification of all relevant flows of materials in a temporally and spatially precisely delimited system and balancing of the materials within this system". The identification of all relevant material flows in the system under consideration is carried out using a "bottom-up" approach in order to be able to extrapolate the current stock of raw materials used and subsequently the future stock.

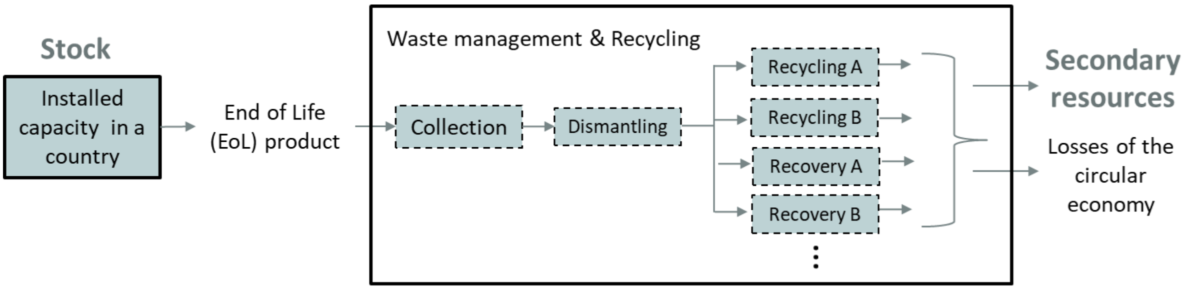
The material composition between the product types used can vary greatly, which is why it was necessary to determine the product types used in Austria based on market volumes. For this purpose, the market situation in Austria was examined in more detail and a market mix of the technologies used in PV (thin-film or silicon-based modules) and wind turbines (with gearbox or gearless) was created, which was mapped by certain indicator products (e.g. a 1.6 m$^2$ PV module with 60 silicon cells of 242 cm$^2$ each and a thickness of 200 µm). Indicator products were used to narrow down the data pool of the material composition of each product. Material intensity and composition were determined for the identified indicator products with a focus on metals, plastics and other mass-relevant fractions. The material composition was determined in a stepwise procedure, starting with the composition of the main components via the specific subcomponents to a detailed material catalogue of individual components. Thus, the MFA is carried out at both the so-called goods and materials level.

The identified indicator products are intended to reflect the market situation in Austria. The selection for the market mix is based on installed systems in 2019, taking into account the trends of previous years from 2010 onwards. In order to fill information gaps, interviews were conducted with experts from the PV sector in Austria (e.g. Photovoltaic Austria, FH Technikum Wien) as well as from the wind sector – mainly wind plant operators – especially on topics such as the size of installed PV plants, the type of mounting systems installed, the situation of PV home storage systems, the use of gearless wind turbines or wind turbines with gearboxes, and future developments.

The material composition in combination with the market mix used in Austria and the installed plants lead to material stock flows that are currently installed in Austria. This wind turbine and PV plant stock is referred to as the (anthropogenic) "stock". Since the overall objective is to determine the secondary resource potential within the country's borders, all mass flows are related to installed capacity. The reference quantity for PV plants was taken as Watt peak (Wp), which represents the maximum (peak) power of PV modules under test conditions. For wind energy, the reference value Watt (W) was used. The potential of secondary resources that would theoretically be available for recovery at the end-of-waste or end-of-life of the system is determined using several recycling scenarios. The specific collection system is not discussed in detail and the return rate is assumed to be 100% in a simplified manner.

The focus for the identification of recyclable materials or groups of materials is on metals, such as steel, aluminium, copper, as well as precious and special metals, such as gold, silver, palladium, tantalum, and critical raw materials, such as lithium and cobalt, as well as high-mass fractions, such as glass fibre or carbon fibre reinforced plastic (GFP or CFRP). This takes into account the goal of the EU circular economy package to treat these secondary raw materials like primary raw materials as anthropogenic stock. Material recycling is the main focus here. All other possible disposal routes, such as thermal recycling, are cited as losses for the raw materials economy. A schematic representation of the MFA is illustrated in Figure 1.

Figure 1: **Schematic representation of the material flow analysis**



Source: Own compilation.

## 4.2 Data sources for the MFA

For the three product systems under consideration – photovoltaic plants, wind turbines and electric vehicles – all components or parts are taken into account as far as possible that are necessary for the operation of these plants, which also form the system boundaries of the MFA. The scope of a PV plant therefore includes the PV module, but also the devices for mounting the modules, the electronic and electrical components used (inverters, charge controllers), cables and, if applicable, a battery. In the case of wind turbines, the tower, the nacelle and the rotor blades, as well as the installed electronics and the transformer and the foundation required for the statics are also taken into account. For electric vehicles, the whole chassis was considered with special focus on electric motor, battery and powertrain.

The material composition data was mainly taken from LCA studies (Life Cycle Assessment) as it is a good documentation of the data used in the respective LCA inventories (Life Cycle Inventories). The difference between the data used for a LCA and the mass flows used in this study is that this LCA inventory includes cleaning or operating materials, soldering fluxes, packaging materials and the energy required for manufacturing, material losses and waste in addition to the material input. Thus, for this MFA, only materials that are built into the product systems are included.

The material composition can vary depending on the PV plant type due to different designs and different use of type and quantity of materials or wind turbine size and type. Consequently, the data sets in individual studies can differ greatly. Data on multicrystalline silicon modules are mainly available in Kranert et al. (2012), Jungbluth et al. (2009), De Wild-Scholten (2014) and Frischknecht et al. (2015). However, the source of the data reported in Kranert et al. (2012) is unknown. In contrast, the data from Jungbluth et al. (2009) are updated in De Wild-Scholten (2014) with regard to reduced wafer (semiconductor wafer) thickness, improved conversion efficiency and novel silicon raw materials and wafer processes. Frischknecht et al. (2015), a report by the Photovoltaic Power Systems Programme (IEA PVPS) of the International Energy Agency, again refers to data from De Wild-Scholten (2014). As a conclusion, data from Frischknecht et al. (2015) were used for this study.

Life cycle assessments of HIT cells are available in Louwen et al. (2015) and Olson et al. (2011). A monocrystalline silicon wafer was used for the HIT. In both publications, eco-inventory data (Ecoinvent 2019) and the material composition of HIT is similar to the monocrystalline cells reported in Stolz et al. (2017). However, the cell efficiency was adjusted to 20% as reported in Louwen et al. (2015).

The material composition of an inverter with 2500 W nominal power at an average total weight of 18.5 kg was used from the composition given in Jungbluth et al. (2009). The composition was supplemented by the material and mass proportions of the electronic components (capacitors, circuit boards, etc.) from Hischier et al. (2007a and 2007b). On this basis, the key figure of 10 kg inverter per kWp could be determined.

LCA studies on wind turbines exist, for example, by Ardente et al. (2008) on an Italian wind farm with 11 turbines of 660 kW each, by Guezuraga et al. (2012) on a 2 MW turbine with gearbox and a 1.8 MW gearless turbine, but also by the manufacturers themselves such as Garrett and Rønde (2014) and Vestas (2015) on 2 MW turbines, and by Vestas (2017) on 3.45 MW turbines. All studies have in common that the composition is only given at the level of the main components and not the subcomponents. In order to cover the Austrian situation as well as possible, the most recent data from Vestas (2017) was used, as the manufacturer Vestas has the greatest market relevance in Austria after Enercon. Furthermore, this study takes into account the trend towards higher MW output per turbine. The hub height of the Vestas turbines is 94 m and the rotor diameter is 112 m. These sizes are representative for the installed turbines in Austria, as in the meantime the average rotor diameter of the new installed turbines is 114 mand the tower height is about 120 m. Since the electronics were included in the study by Vestas (2017), but do not appear in the desired level of detail of the subcomponents, the electronic systems must be completed with data from Hischier et al. (2007a and 2007b). In addition, the tower must also be adapted for the Austrian mix, as more and more hybrid towers (steel and concrete) are also being installed. According to interview partners in this industry, hybrid towers (steel and concrete) tend to be erected at a height of >120 m, and steel towers at <120 m.

Hawkins et al. (2013) provides a transparent life cycle inventory of electric vehicles including detailed material contents. However, the necessary level of detail is not provided in the data inventory. So, data for electric motor, powertrain and battery was collected from Ellingsen (2014) and Ecoinvent 3.6 (Ecoinvent 2019).

## 4.3 Economic Analysis and the Model WIFO.DYNK

For the stock development of PV, wind and LIB (lithium-ion batteries) from electric vehicles regarding the economic evaluation of the recycling of renewable energy technologies in Austria, the Transition Scenario (TRANS) is applied as the central model assumption (Meyer et al. 2020; Meyer et al. 2018a, UBA 2017). TRANS is an energy scenario for Austria covering the period 2015-2050. It describes a possible development of the Austrian economy with the goal of climate neutrality, i.e. a reduction of energy-related greenhouse gas (GHG) emissions by at least 80-95% (2050/1990). It thus follows the goal of the Paris Climate Agreement (COP21) to limit global warming to well below +2°C. TRANS focuses on energy efficiency in capital stocks and encompasses basic resource conservation strategies in the steel sector. Thus, not only a highly efficient renewable energy system is deployed, but also measures in non-energy sectors (e.g. in the area of spatial planning) are underpinned, which imply changes in demand patterns, e.g. in mobility behavior. Central assumptions of the Transition scenario are:

- All economies take measures and action to comply with the Paris Climate Agreement (global climate protection scenario).
- The deployment of renewable energy technologies is moderated by increasing $CO_2$ prices.
- An eco-social tax reform creates incentives for climate mitigation and promotes social compensation.
- $CO_2$ price increases (2015: 8 €/t; 2020: 15 €/t; 2030: 40 €/t; 2050: 200 €/t) follow the World Energy Outlook 2016 (IEA 2016)[1].

The resulting stocks of renewable energy technologies in TRANS serve as a baseline to quantify relevant material flows, and to the development of recycling scenarios (ROSE (Base/High), **chapter 9.2**).

The economic analysis of this study focuses on the impact of the domestic installation of recycling facilities. The analysis comprises two steps. In the first step, the profitability of EoL material recycling from a microeconomic perspective is investigated. The common approach is to derive the net present value (NPV). The NPV is a form of discounted cash flow analysis that resembles the sum of the present values of individual cash flow and is used to estimate the profitability of an investment project. Several examples can be found on PV recycling (D'Adamo et al. 2017, Choi et al. 2014, Cucciella et al. 2015a, 2015b; Deng et al. 2019), lithium-ion battery recycling (Thies et al. 2018, Hoyer et al. 2013, Rohr et al. 2017), and, more rarely, on recycling of carbon fabric of wind power plants (Sommer and Walther 2021). In many cases, the investment into a stylized or average recycling facility based on investment costs, operation costs and revenues from extracted secondary materials are applied to calculate the NPV. The NPV calculation applied in this work is as follows:

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[1] Since the work for this study has started in 2018 and the simulations were executed in early 2021, later decisions regarding $CO_2$ prices within the European Emission Trading System or outside were not considered.

$$NPV = \sum_{t=t}^{T} \frac{CF_t}{(1+r)^t}$$

$$CF_t = \sum_{t=1}^{N} CF_t^{Invest} + CF_t^{FixOp} + CF_t^{VarOp} + CF_t^{Factors} \qquad (1)$$

Where CF = net cash flow, $CF^{Invest}$ = cash outflow for investment, $CF^{FixOp}$ = cash outflow for fixed operation costs, $CF^{VarOp}$ = cash outflow for variable operation costs, $CF^{factors}$ = cash flow related to income (recovered materials) and expenses (waste disposal costs) from output factors.

A negative NPV signifies that the investment did not pay back in a specific period which is typically 10 years (D'Adamo et al. 2017). A positive NPV shows that the project is profitable and gains profits for the investor. The results of this microeconomic analysis will comprise the NPV of the investigated recycling technologies (**section 9.1**) per processed mass unit (tons) and a variation of the revenues due to price fluctuations (**section 9.1.1**)

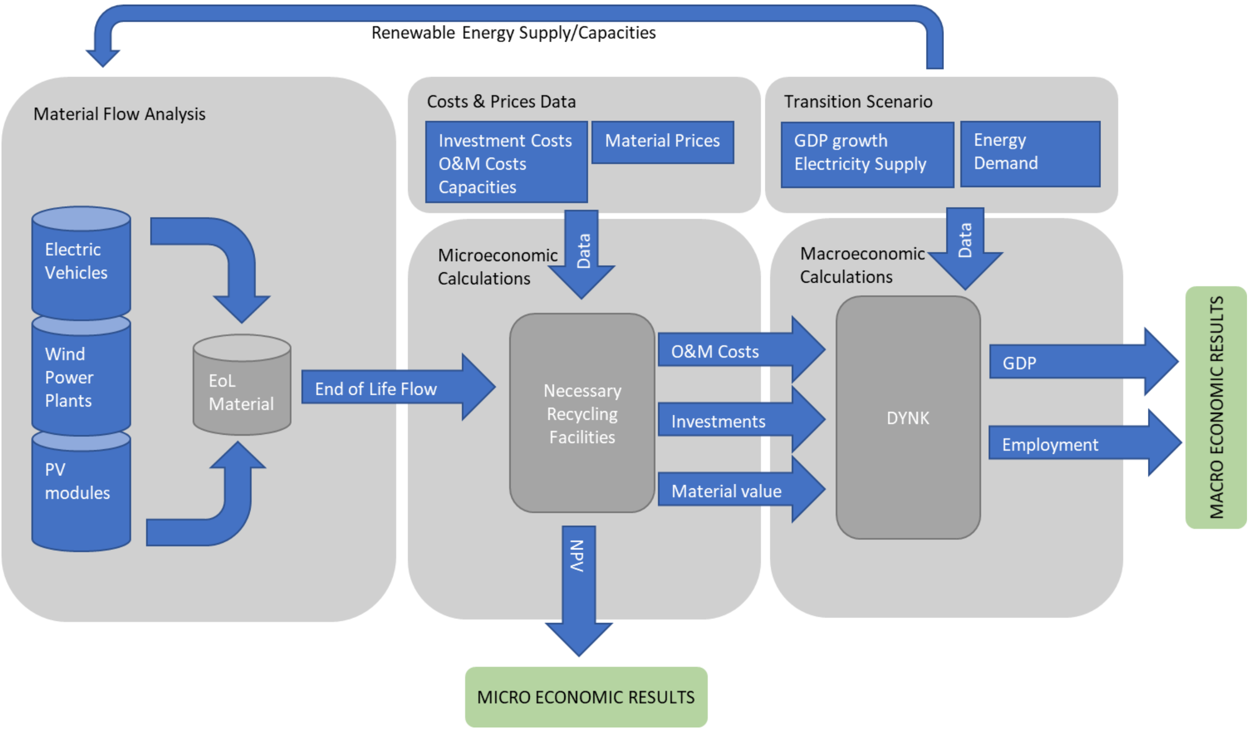
The second step is the analysis from a macroeconomic point of view. The estimation of the macroeconomic effects of the investment and operation of recycling plants for Lithium-Ion Batteries, photovoltaic panels and wind power generators is performed using a traditional input-output analysis implemented in the WIFO.DYNK (Dynamic New Keynesian) model (Kirchner et al. 2019). The WIFO.DYNK model approach is modular, has an input-output model core, but resembles DSGE (Dynamic Stochastic General Equilibrium) models in that it describes an explicit adjustment path that approaches equilibrium in the long run. The term "New Keynesian" refers to the existence of full employment in the long run, which is not achieved in the short run due to institutional rigidities. These rigidities include consumer budget constraints (derived from the permanent income hypothetical), wage rigidities (labor market competition) and imperfect capital markets. Depending on the distance to long-term equilibrium, the responses of macroeconomic aggregates (due to exogenous shocks) may differ substantially.

A key application of WIFO.DYNK is the ability to attach changed physical material flows to monetary structures of the input-output table and analyze the associated economic effects. This material flow change can come from different backgrounds. For example, it can be the re-use of previously disposed or exported products, leading to changed import and export flows, or the uplift of secondary materials (e.g. scrap, waste paper), whose re-use reduces the demand for primary materials (e.g. wood, and ore). In addition to the economic effects of material flow change, there are the effects of collection activities, investment in treatment facilities, and their operation.

For the present project, the modules simulating the aforementioned "New Keynesian" and dynamic elements were not activated, as this would have influenced the results of parameters (e.g. unemployment rate, labor force, state of technical progress) and would thus have made them more difficult to comprehend. This simplified WIFO.DYNK thus corresponds to an input-output analysis (IO analysis) extended by endogenous consumption. On the basis of this, it is possible to show how many goods are produced along the intermediate input chain in an economy when investments are made or when structures change, e.g. through the operation of a new recycling plant. The effects that are represented in this way include direct, indirect, and induced effects. Direct effects refer to investments and operation of the facilities. Indirect effects take into account the production of goods and employment generated by the changed demand structure and the production of intermediate inputs in other sectors required for this purpose. The increase in income associated with increased production has a positive effect on private consumption, which again affects demand. This effect can be interpreted as a "consumption-induced effect."

In this study the model will be used to estimate the macroeconomic effects of the existence of recycling facilities in Austria. Therefore, the WIFO.DYNK model runs iteratively until 2050 as a reference scenario using growth and energy intensity information from the Transition Scenario (UBA 2017). The counterfactual scenarios use prepared datasets (microeconomic calculations) for simulating the impact of recycling facilities. The deviation from the reference path (in GDP value and employment) shows the macroeconomic impact. This prepared data comprises on one hand investment activities, operation structures, output composition (recovered materials) and output values (material prices) of the recycling facilities and on the other hand the assumed EoL flows. The data set on costs and prices assembled in this project are outlined in **sections 4.4** and **4.5** and the potential EoL material in accordance with the Transition Scenario in **section 9.2**. **Figure 22** summarizes the connection between the assembled data sets.

**Figure 22: Schematic overview of the economic analysis**



Source: Own compilation.

## 4.4 Resource Prices

Many factors influence the supply of raw material and its price developments. A high global demand of functional materials for the energy transition does not necessarily convert to a future of raw material bottleneck and high resource prices. This development depends on the overall supply-demand balance. High demand may raise resource prices, making exploration, mining and refining projects as well as substitution and recycling commercially viable and attractive (European Commission 2020c).

Raw materials are a significant element in the cost structure of many renewable energy technologies. In the case of lithium-ion batteries (LIB), technology learning and economies of scale have pushed down overall costs by 90% over the past decade. This translates into a larger share of raw material costs in the cost structure, accounting for some 50%-70% of total battery costs, up from 40%-50% five years ago. Higher mineral prices could therefore have a significant effect: a doubling of lithium or nickel prices would induce a 6% increase in battery costs (IEA 2021).

In the economic analysis of EoL mass flow recycling and the regaining of materials, the prices for primary (raw) or secondary (scrap) materials play an inverse role as they define the potential revenue from the recycling process. In this work we assembled a set of material prices (Annex A) from the literature which are relevant for outputs of the recycling process.

displays the prices for the year 2020 which will be used in the economic analysis. Prices in vary from very high values for gold (over 50 Mio. €/t) to negative values of –500 €/t. The latter represent the disposal costs for hazardous output, i.e. residual waste.

As stated above, price fluctuations of primary and secondary materials can be strong and have an immediate impact on the profitability of a recycling facility. To account for that, we follow Deng et al. (2019) who analyzed the influence of price fluctuations via the usage of standard deviations and a "Monte Carlo" simulation. This paper applies over 50.000 price variations and calculates the impact on costs and revenues. This way, the assumed price fluctuations can be translated into a bandwidth of possible revenues for the recycling processes.

Table 1: **Material prices in 2020 and assumed standard deviation**

| | Price<br>€/ton | Standard deviation<br>% | Source<br>Prices | <br>Deviation |
|---|---|---|---|---|
| Glass scrap | 76 | 20 | [6] | [9] |
| Aluminium (Al) scrap | 1,038 | 13 | [6] | [9] |
| Copper (Cu) scrap | 3,665 | 25 | [6] | [9] |
| Steel scrap | 700 | 17 | [6] | [9] |
| Gold (Au) | 50,337,923 | 14 | [5] | [9] |
| Silver (Ag) | 583,966 | 11 | [5] | [9] |
| Silicone (proxy Ferrosilicone) | 1,480 | 18 | [4] | [9] |
| Manganese (Mn) | 1,500 | 9 | [4] | [10] |
| Nickel (Ni) | 12,194 | 9 | [5] | [9] |
| Lithium hexafluorphophate (LFP) | 200 | 54 | [8] | [10] |
| Cobalt (Co) | 28,900 | 1 | [7] | [9] |
| Cadmium (Cd) | 2,014 | 13 | [3] | [9] |
| Gallium (Ga) | 228,580 | 7 | [7] | [9] |
| Indium (In) | 97,410 | 15 | [4] | [9] |
| Molybdenum (Mo) | 18,386 | 1 | [7] | [9] |
| Tellurium (Te) | 63,494 | 17 | [3] | [9] |
| Tin scrap (Sn) | 11,738 | 14 | [6] | [9] |
| Selenium (Se) | 21,588 | 40 | [2] | [9] |
| Zinc (Zn) | 2,189 | 6 | [7] | [9] |
| Plastics | 90 | 7 | [1] | [9] |
| Electronic Scrap / Junction box | 300 | 16 | [1] | Cu & Plastics |
| NiCoMn 111 hydroxide | 800 | 6 | [1] | Mean of NiCoMn |
| Waste treatment/disposal expenses | -150 | 0 | [1] | none |
| Hazardous Waste disposal expenses | -500 | 0 | [1] | none |

Source: Own compilation. [1] Thies et al. (2018), Table 15.4, Realistic Assumptions – [2] metal.com (2021) – [3] statista.de (2021a) – [4] statista.de – (2021b) – [5] Worldbank (2021) – [6] COMTRADE (2021) – [7] tradingeconomics.com (2021) – [8] alibaba (2021) – [9] Cucciella (2015a) – [10] Own calculations based on prices in Annex Aa.

## 4.5 Recycling Costs

The costs of recycling in the investigated literature in most cases comprise investment costs in whole facility complexes (D'Adamo et al. 2017, or Cucciella et al. 2015b) or different components of the recycling chain (Thies et al. 2018, or Deng et al. 2019) as well as operation costs (fixed and variable) and sometimes the costs of waste disposal. Here we treat waste disposal costs as a negative output of the process that diminishes profits but not as part of the costs.

In case of wind power generation, we did not investigate the economic effects of recycling these installations. Even though the installed capacities will be part of the EoL waste stream, there is little literature on recycling costs of these materials. The reason might be, that wind power plants are rather exported than recycled at the moment as stated in UBA (2019). Furthermore, for some parts like the blades, recycling technologies are relatively new and therefore expensive (Sommer and Walther 2021). Consequently, the economic analysis in **chapter 9** comprises only the recycling of PV installations and electric vehicles because there is no sufficient data on recycling wind power plants, and it does not seem to be economically feasible soon.

**Table 2** summarizes the main cost components of the recycling of PV and EV for two cases, Basic Recycling and High Efficiency recycling. This resembles four hypothetical stylized recycling facilities. Each EoL material flow (PV and EV) is divided into three groups. In the case of PV, we differentiate between material flows of the PV module, the metals for mounting and the Balance of System (BOS) part. In case of the electric vehicle it is the lithium-Ion battery cell, the auxiliary system of the battery (management system and cooling) and the remaining vehicle.

The costs for Basic Recycling of LIB is based on Thies et al. (2018) and comprises transport, handling, disassembly of the cell, the recovery of several secondary materials and black mass, which contains valuable metals as nickel, cobalt and manganese. The High Efficiency recycling adds a hydro/pyrometallurgical process that recovers these valuable metals from the black mass. Both facilities have a capacity of 6.000 tons per year. The other parts of the EV, the management system and cooling of the LIB as well as the remaining vehicle are assumed to be outsourced to existing facilities where the materials are recovered. For this we assume process costs for metal and electric waste treatment based on a study on Austria's waste economy (TU Wien 2015). The revenues of the regained materials are still accounted to the hypothetical recycling facility.

Table 2: **Cost data of recycling facilities**

| | | | Electric Vehicles | | | Photovoltaic Panel | | |
|---|---|---|---|---|---|---|---|---|
| | | | LIB cells | LIB BMS & Cooling | Vehicle | Module | Mounting | BOS |
| **Basic recycling rate** | | | | | | | | |
| | Facility construction cost | Mio.€ | 10 | – | – | 2 | – | – |
| | Capacity | t/a | 6,000 | – | – | 2,000 | – | – |
| | O&M fix | €/annual ton capacity | 125 | – | – | 17 | – | – |
| | O&M variable | €/t | 641 | 225 | 100 | 368 | 55 | 225 |
| **High recycling rate** | | | | | | | | |
| | Facility construction cost | Mio.€ | 20 | – | – | 12 | – | – |
| | Capacity | t/a | 6,000 | – | – | 2,000 | – | – |
| | O&M fix | €/annual ton capacity | 295 | – | – | 505 | – | – |
| | O&M variable | €/t | 641 | 225 | 100 | 531 | 55 | 225 |

Source: Own compilation.

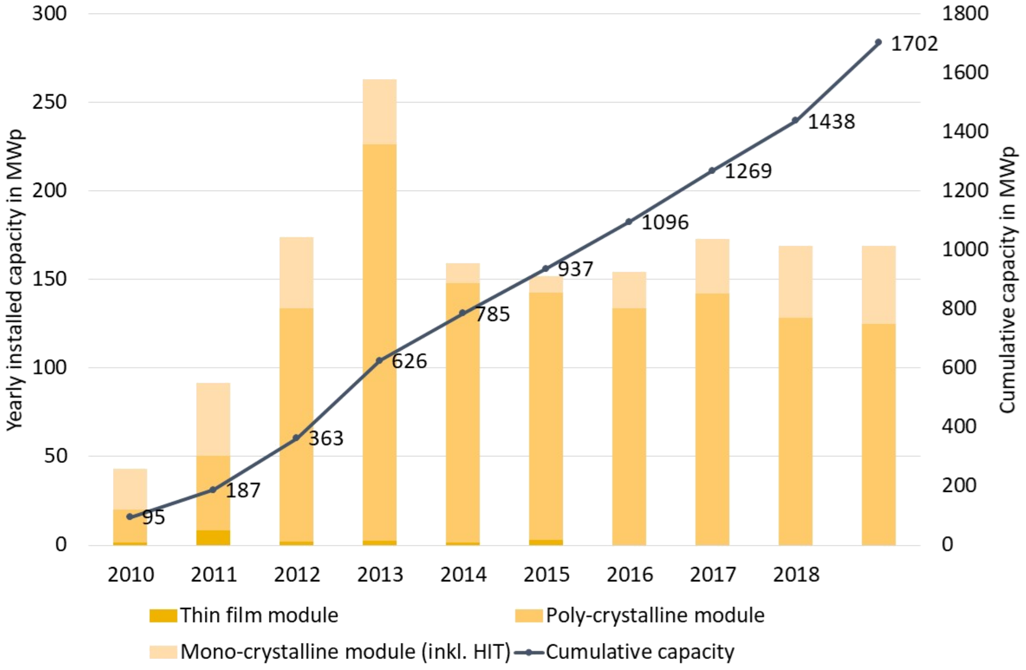
The costs of PV module recycling are based on Cucciella (2015) and represent the case of a facility with a capacity of 2.000 tons per year. As fixed costs we assume the process costs and as variable costs the transport expenses EoL devices. Some other literature assumes capacities of up to 20.000 t/a and consequently resembles much lower unitary capital costs (Choi et al. 2014). Due to the size of Austria, this has not been analyzed. Like EV the treatment of auxiliary elements such as the mounting (shredder) and the Balance of Systems (BOS), WEEE treatment is outsourced to existing facilities, and the treatment expenses set in accordance with TU Wien (2015).

# 5. Scenario Development

## 5.1 Status-Quo of PV, Wind and E-vehicles

The number of PV modules installed annually peaked in 2013 at over 250 MWp and then remained constant with annual installation rates between 150 and 160 MWp as shown in Figure **3**. By the end of 2019, a cumulative number of installed PV systems in Austria totalling 1.7 GWp had been reached. Installed panel types in Austria are mainly polycrystalline silicon cells with a market share of 74%, followed by monocrystalline silicon cells with 26% (Biermayr et al. 2020). So-called HIT solar cells ("Hetherojunction with Intrinsic Thin-Layer") are listed under the category of monocrystalline cells, as their internal cell structure includes amorphous silicon in addition to crystalline silicon but have different electrode materials. Thin-film cells made of cadmium telluride (CdTe) or copper indium gallium diselenide (CIGS) are of rather minor importance in Austria, with a market share of less than 1%. In addition, the use of energy storage systems to increase self-consumption of electricity is playing an increasingly important role. In 2017, 30% of newly installed PV systems were already equipped with energy storage systems (Fischer and Leonhartsberger 2019).

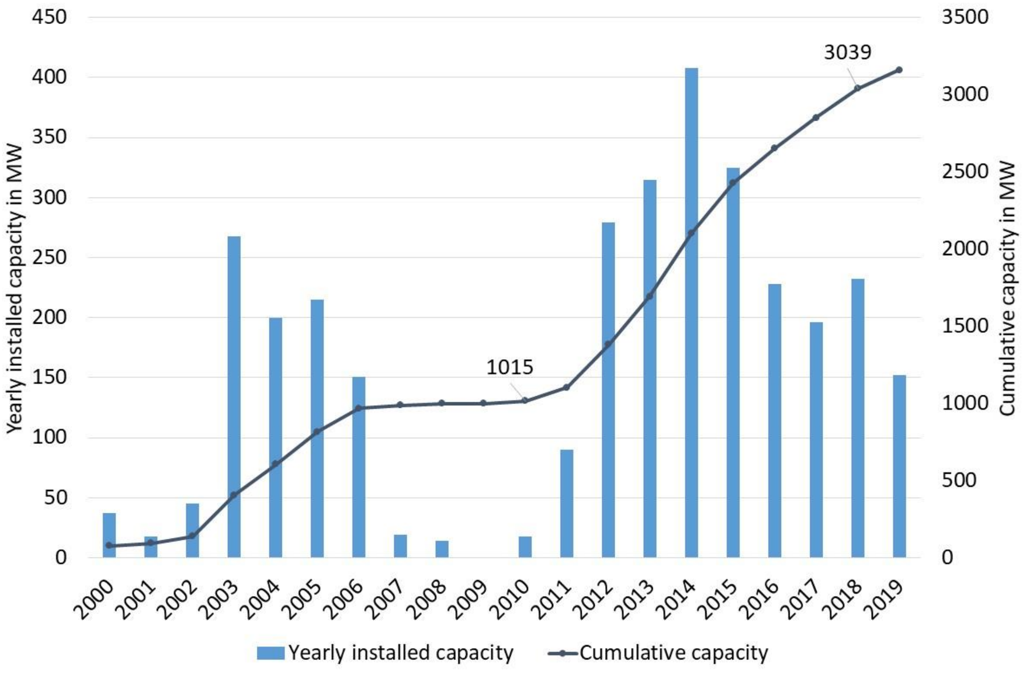
Figure 3: **Development of existing and newly installed PV plants in Austria, 2010-2018**



Source: Own adaptation based on Biermayr et al. (2020).

Wind turbines had a first boom in Austria in the years 2003 to 2006 and reached a peak in new installations in 2014 after a downtime due to the economic crisis. Wind energy has been a growing industry in Austria over the last 10 years as **Figure 4** illustrates, reaching an installed nominal capacity of more than 3 GW in 2019, produced in a total of 1,340 turbines. A trend towards lower specific generator power and larger rotor diameters was observed. While the average turbine capacity of newly installed turbines was still 1.78 MW per turbine in 2004, it was already 2.73 MW per turbine in 2013 (Winkelmeier et al. 2014). The main wind turbines installed in Austria in recent years amounted to 3 MW per turbine (Biermayr et al. 2020). It should also be mentioned that so-called repowering (the replacement of old wind turbines with new ones in existing wind farms) is gaining importance in Austria. For example, in Burgenland 26 wind turbines with a total capacity of 46.8 MW, which were erected in 2003, will be replaced by 13 new wind turbines and the total capacity will be increased to 65 MW at the same time. In summary two main wind turbine groups installed in Austria: Turbines with gearboxes and gearless turbines with direct drive. Currently, about two thirds of the installed wind turbines are without gearbox and one third with gearbox (Biermayr et al. 2020). According to IG Windkraft documented in Einsiedler (2017), as of 2017 only nine wind turbines with permanent magnets containing the critical raw material neodymium (Nd) are in operation in Austria.

Figure 4: **Development of existing and newly installed wind turbines in Austria, 2000-2019**



Source: Own adaptation based on Biermayr et al. (2020).

The group of electric private cars include battery electric vehicles (BEV), fuel cell electric vehicles (FCEV), plug-in hybrid electric vehicles (PHEV) and electric scooter. In Austria, the relevance of electric driven transport vehicles, such as electric buses, and electric trucks is still low considering that currently 30,000 e-cars compared to 2,300 e-busses or trucks are registered

(Status March 2019). The electric vehicle fleet in Austria is currently (Status March 2019) dominated by BEV with a share of 57% (23,242 cars[2]) and e-motorbikes with a share of 22% (9,005 pieces). BEV have a share of 0.47%[2] in the total passenger car fleet in Austria. However, this share is expected to increase in upcoming years.

The highest market share of BEV in Austria has Tesla with 36.8%, followed by BMW with 12.5% and Hyundai with 10.7% (Bundesministerium Verkehr, 2019). The battery capacity of new vehicle types used in Austria range from 18 kWh (Smartfortwo, Smartforfour) to 100 kWh (Tesla Model S 100). The electric demand is though mainly at 13.5-19.3 kWh/100 km, except for some outstanding cars such as Jaguar I-PACE and Audi e-tron with 22.7 and 22.5 kWh/100 km respectively (Autorevue 2019). Considering the average distance per day in Austria of 34 km (Statistik Austria 2016), one BEV demands around 2.5 MWh of electricity per year.

Lithium-ion batteries play an essential role in Europe, around 800,000 tons of car batteries, 190,000 tons of industrial batteries and 160,000 tons of portable batteries (30% rechargeable ones) are placed in the European Union market (Nigl 2016).

## 5.2 Scenarios for Stock Development of PV, Wind and E-Vehicles

According to the current government program, Austria should be climate neutral by 2040 (Austrian Federal Government 2020). For this reason, the Transition scenario, which was originally set to 2050, was compacted to 2040. Furthermore, the starting values in 2020 are based on real values from 2019 and the assumption that the expansion is on average over the last five years. **Figure 5** and **Figure 6** show the expected amounts for photovoltaic and wind power plants as well as for electric vehicles in the Transition scenario.

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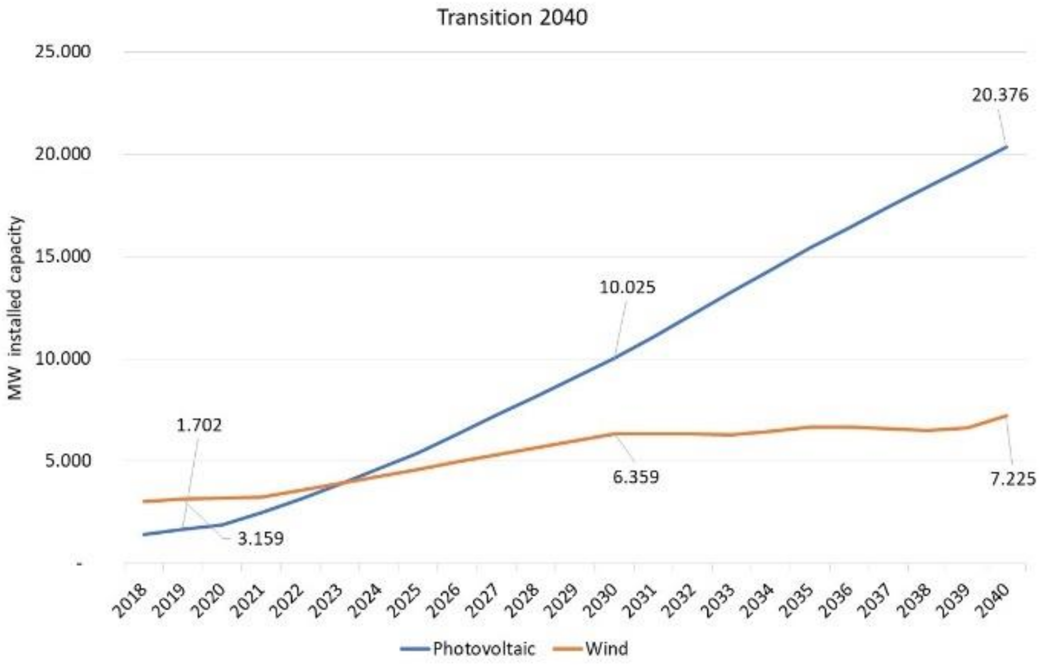
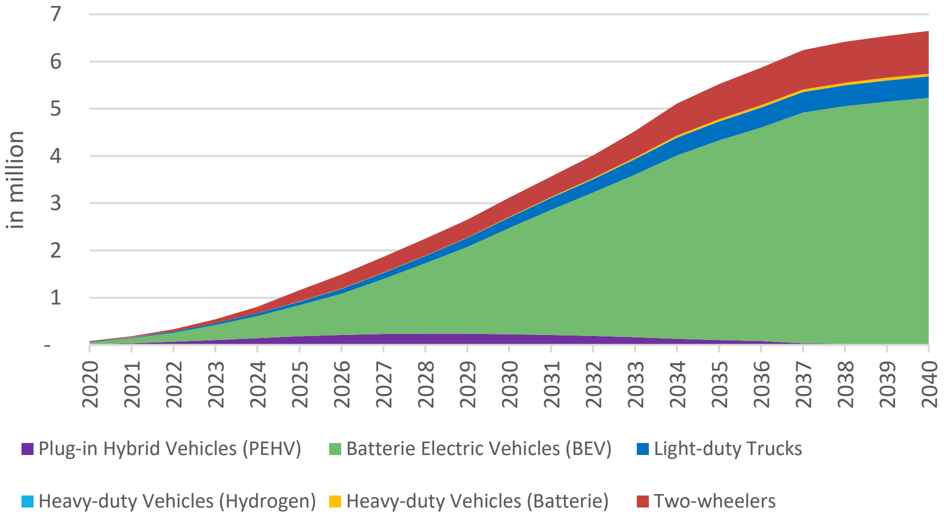
[2] Status October 2021: 70,184 cars. This amounts to a share of 1.4% in the passenger car fleet.

Figure 5: **Development of the installed capacity of PV and wind power plants, Transition scenario**



Source: UBA 2017, own compilation.

Figure 6: **Development of the e-vehicle stock, Transition scenario 2040**



Source: UBA 2017, own adaptation.

### 5.3 Scenarios for Recycling

Currently, most wind turbines and PV plants are still in operation and have not yet had to be demolished or disposed of. To forecast the future amount of waste, a functional lifetime of 30 years can generally be assumed for PV plants and 20 to 30 years for wind turbines (Bio Intelligence Service 2011; Stolz et al. 2017). A general refurbishment of wind turbines could extend the lifetime to a further 15 years (Wilburn 2011). However, the economic lifetime of these plants is usually shorter, which is why they are usually dismantled earlier (e.g. currently through repowering of wind turbines) in order to be rebuilt and re-used at other locations (usually also outside of Austria). For this study, a shortened lifetime of 20 years is therefore assumed for both systems.

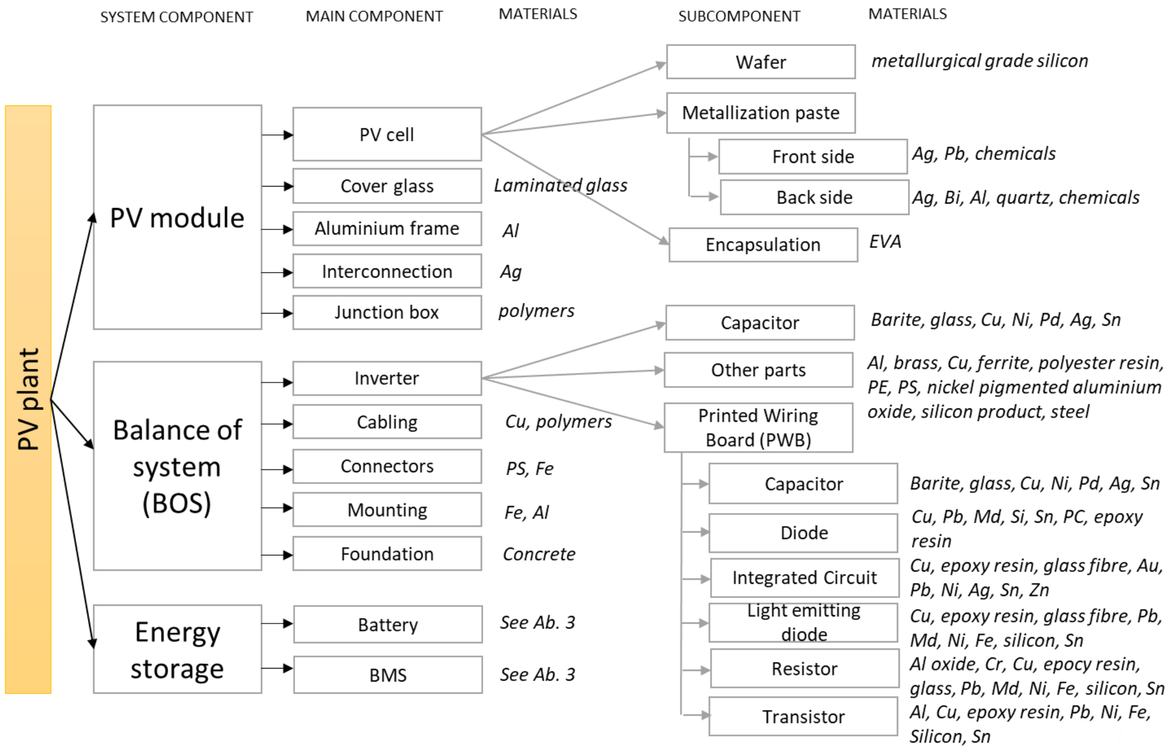
Due to the low waste volumes, high-quality recycling cannot yet be carried out either, as relevant recycling processes can often only be operated economically with high utilisation and large capacity sizes. However, in the near future, taking into account the high growth rates of PV plants, wind turbines as well as e-vehicles, the waste volumes will increase drastically and consequently the recycling routes will also change. Therefore, this study distinguishes between the Base Case Recycling and the High Efficiency Recycling scenario. The former refers to the status quo of recycling and disposal of product systems in Austria. The High Efficiency Recycling scenario refers to recycling solutions that would already be technically possible from today's perspective but are not currently implemented for economic or other reasons. This also refers to possibilities for high-quality recovery of secondary resources.

It should also be noted that in these scenarios recycling refers exclusively to material recycling and not to thermal recycling. This primarily concerns metals, and secondarily plastics from individual components, insofar as they can be dismantled manually and are available in larger quantities (e.g. rotor blades). The recycling scenarios for PV plants refer to data from Ardente et al. (2019) and for wind turbines from Vestas (2017) for the status quo and from research projects documented in Jensen and Skelton (2018) for the recycling of rotor blades.

## 6. Material Composition of Renewable Energy Technologies

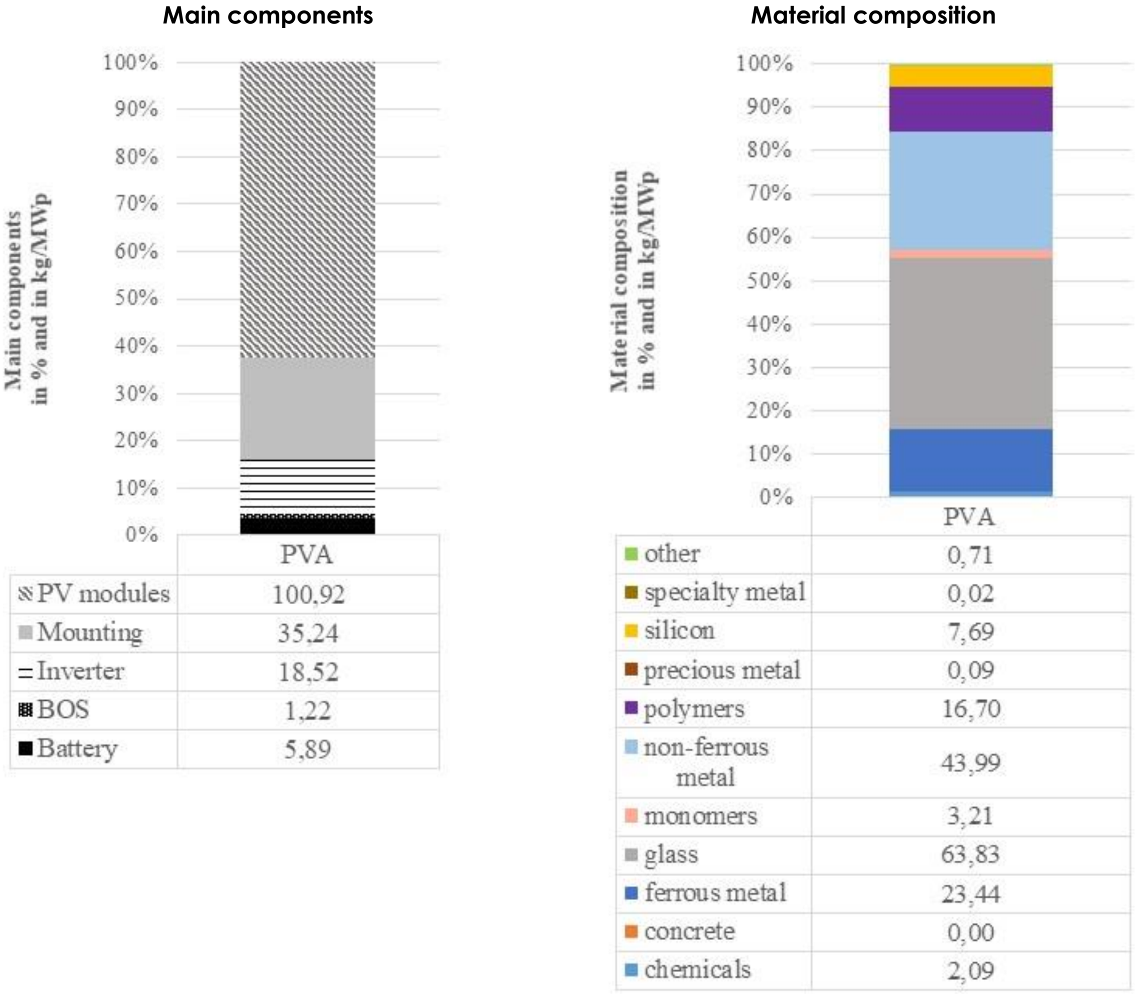
As the market mix of PV plants in Austria consists mainly of polycrystalline (74%) and monocrystalline (26%) silicon cells, thin-film modules were not considered. In general, silicon-based PV cells relevant to this study are doped with boron, using phosphorus diffusion to create emitters on the surface of the wafers. An anti-reflective layer (blue to blue-black coloured silicon nitride) on the front surface and metal pastes containing silver, aluminium, lead and cadmium ensure electrical contact of the front and back surfaces of the cell. A plastic film made of ethyl vinyl acetate (EVA) encapsulates the cells behind the glass and a Tedlar® film is used as the back of the module and an aluminium frame to stabilise the module (Kranert et al. 2012). A mixture of polyvinyl fluoride (PVF) and polyethylene terephthalate (PET) is used for the back foil (De Wild-Scholten 2009, 2014). The glass cover has high requirements for transparency, surface reflection and strength and is therefore made of low-iron tempered glass. To calculate the mass, a thickness of 4 mm and a density of 2.5 g/cm³ are assumed in this work. Both the glass and the aluminium frame must guarantee a service life of more than 20 years under severe outdoor environmental conditions. Copper is used to connect the cells together and tin, lead as well as nickel for the coating. A junction box is usually installed on the back of modules and is therefore counted as part of the PV module. Mass-relevant components in PV modules are laminated glass as the main component, but also the mounting made of aluminium rails. On the resource side, silver from the cells and silver and gold from the electronic components are of economic importance. **Figure 7** and **Figure 8** show the characteristic PV material composition, which served as the basis for the mass calculation of the inventory as well as the waste quantities.

Figure 7: **Illustration of the material composition of a PV plant with silicon-based solar cells and energy storage**



Source: based on data from Frischknecht et al. (2015), Louwen et al. (2015), and Hischier et al. (2007a); Hischier et al. (2007b), own compilation.

Figure 8: **Composition of main components and materials of a PV plant**



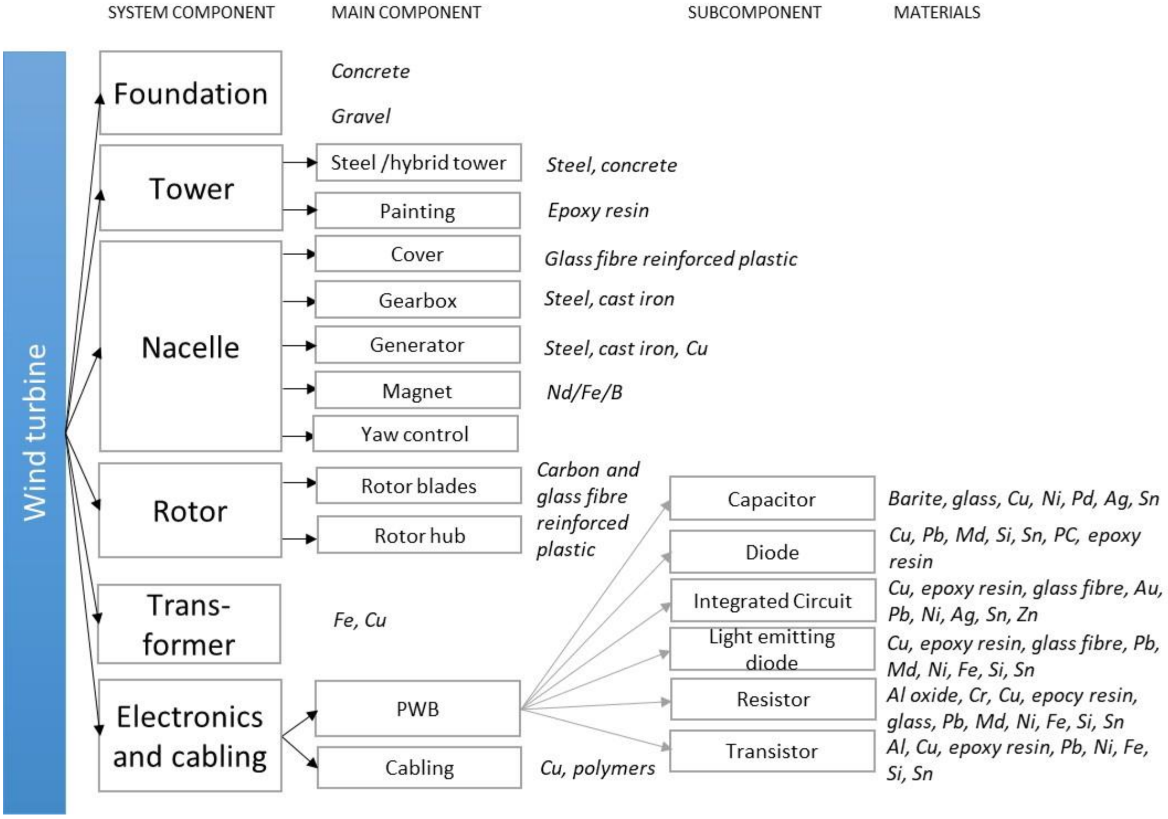
| | PVA |
|---|---|
| ▨ PV modules | 100,92 |
| ■ Mounting | 35,24 |
| = Inverter | 18,52 |
| ▩ BOS | 1,22 |
| ■ Battery | 5,89 |

| | PVA |
|---|---|
| 🟩 other | 0,71 |
| ■ specialty metal | 0,02 |
| 🟨 silicon | 7,69 |
| 🟫 precious metal | 0,09 |
| 🟪 polymers | 16,70 |
| 🟦 non-ferrous metal | 43,99 |
| ■ monomers | 3,21 |
| ■ glass | 63,83 |
| 🟦 ferrous metal | 23,44 |
| 🟧 concrete | 0,00 |
| 🟦 chemicals | 2,09 |

Source: based on data from Frischknecht et al. (2015), Louwen et al. (2015), and Hischier et al. (2007a); Hischier et al. (2007b), own compilation.

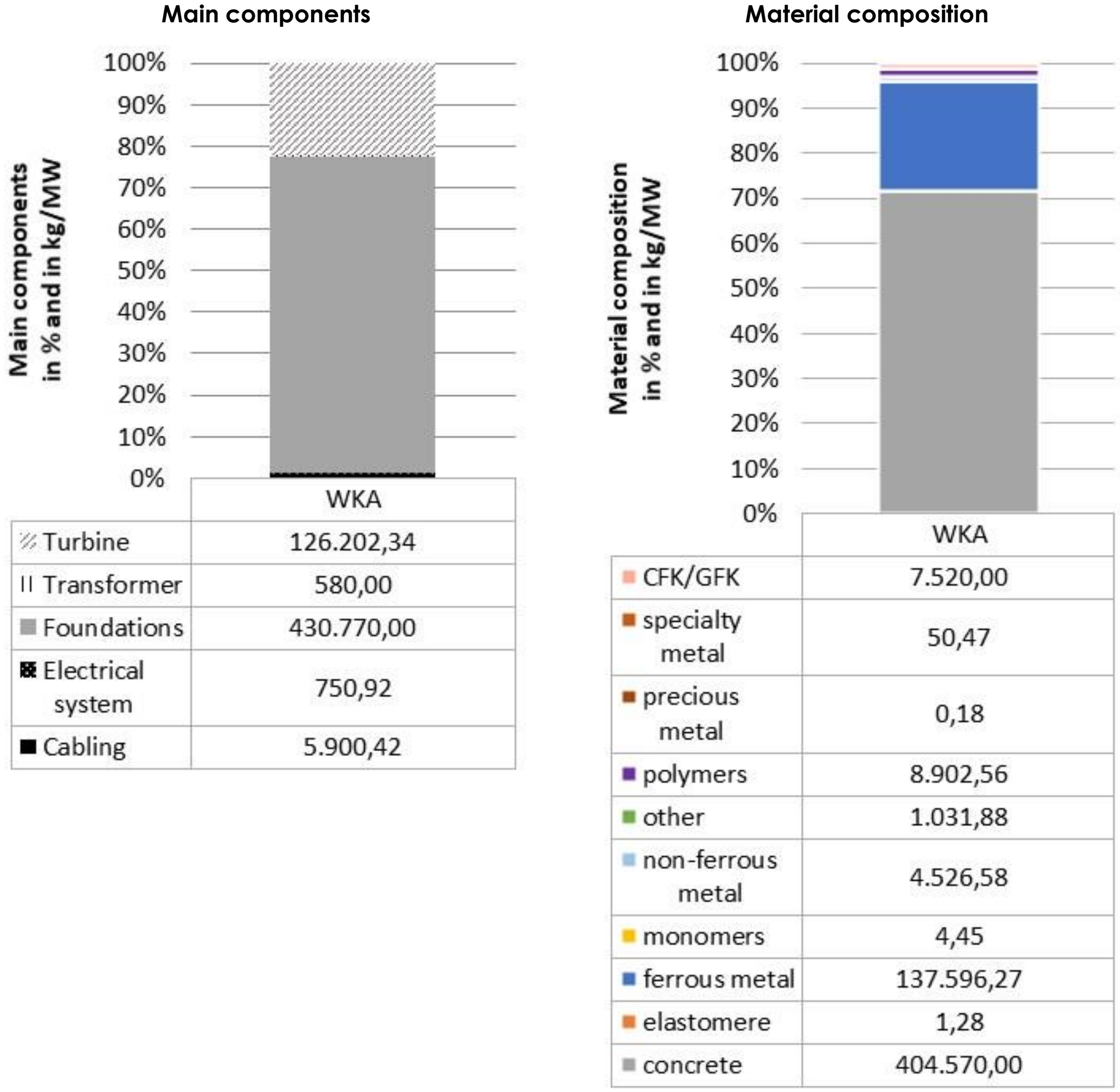
**Figure 9** and **Figure 10** show a typical material composition of a wind turbine. This consists of a foundation and a tower, a nacelle with generator, transformers, a gearbox and electronics, and a rotor hub with three rotor blades. The difference between turbines with gearboxes and gearless turbines is based on the technology used to convert power between the rotor and turbine. Gearless turbines can be equipped with permanent magnets made of neodymium (Luidold 2013). Neodymium is on the EU list of critical raw materials (European Commission 2020b) and is one of the rare earths and is used in the form of neodymium-iron-boron (NdFeB) in gearless wind turbines. The specific mass of these magnets is between 0.5 and 1 ton per MW. The neodymium content in the magnet is around 30% and results in a converted specific mass of 0.15 to 0.30 tons of neodymium per MW (Luidold 2013). It should be noted here that the highly volatile metal market for Nd has become a relevant cost factor for the construction of wind turbines. However, NdFeB magnets are currently only installed in 9 out of 1,340 wind turbines in Austria. The foundation and tower are mass-relevant components consisting of concrete, steel or a concrete-steel construction, the quantity of which is strongly influenced by the hub height, which can range from 80 to 173 m, with rotor diameters in Austria ranging from 72 to 124 m (Biermayr et al. 2020; Winkelmeier et al. 2014). As in PV plant, the electronic components used also play a major role in wind turbines in terms of the installed, metallic resources.

Figure 9: **Illustration of the material composition of a wind turbine**



Source: based on data from Vestas (2017), and Hischier et al. (2007a); Hischier et al. (2007b), own compilation.

Figure 10: **Composition of main components and materials of a wind turbine**



| | WKA |
|---|---|
| ▨ Turbine | 126.202,34 |
| ǁ Transformer | 580,00 |
| ■ Foundations | 430.770,00 |
| ▩ Electrical system | 750,92 |
| ■ Cabling | 5.900,42 |

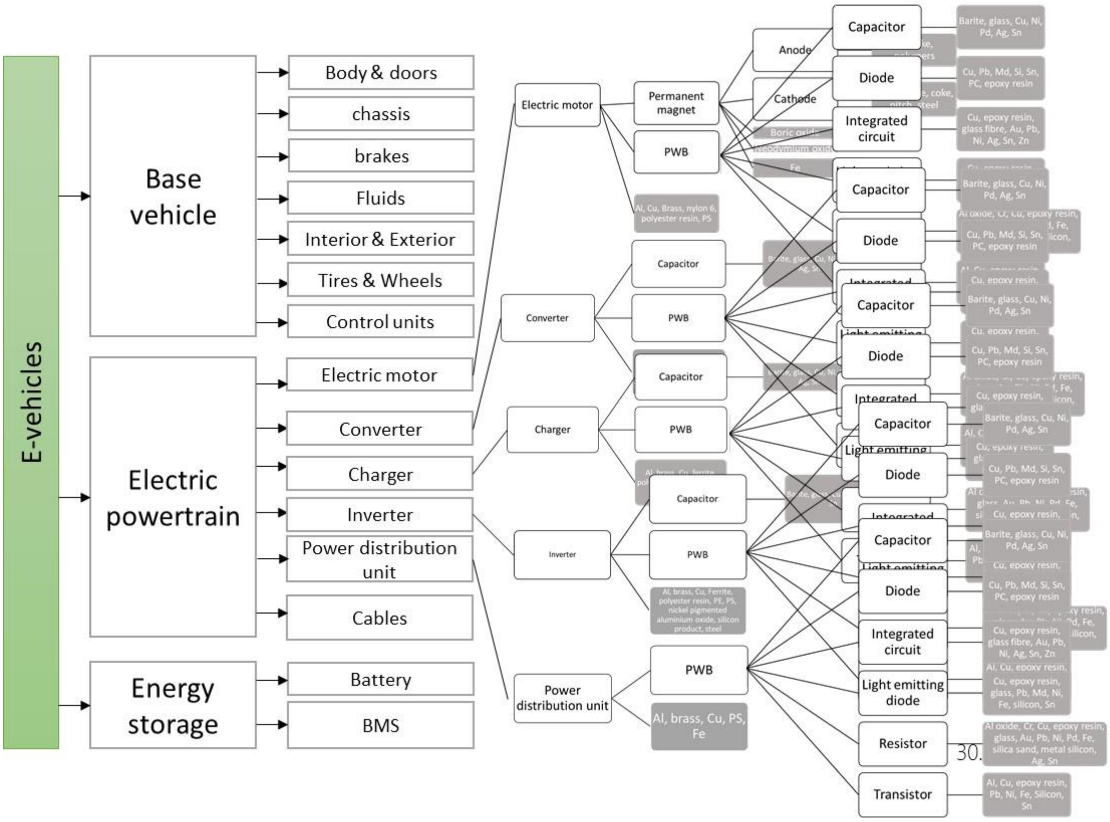
| | WKA |
|---|---|
| ■ CFK/GFK | 7.520,00 |
| ■ specialty metal | 50,47 |
| ■ precious metal | 0,18 |
| ■ polymers | 8.902,56 |
| ■ other | 1.031,88 |
| ■ non-ferrous metal | 4.526,58 |
| ■ monomers | 4,45 |
| ■ ferrous metal | 137.596,27 |
| ■ elastomere | 1,28 |
| ■ concrete | 404.570,00 |

Source: based on data from from Vestas (2017), and Hischier et al. (2007a); Hischier et al. (2007b), own compilation.

**Figure 11** and **Figure 12** show a typical material composition of an electric vehicle. Electric vehicles differ from combustion engines with additional components such as inverter, on-board charger and quick charger plug and a battery system, mainly lithium-ion batteries. Additionally, a household charger plug is recommended to be installed at home. The chassis of electric vehicles has less weight than combustion engines to allow a higher electric range. Therefore, less steel or cast iron is installed in the cars and instead more light-weight metals, such as aluminium, are installed as well as more cables. One of the most relevant components in electric vehicles is the heavy battery system (318 kg in an E-Golf), which need to be replaced during a lifetime of the car in case of decreased capacity. However, in this case the battery is still functioning and can be re-used in e.g battery charging systems for PV plants at households. VDE is estimating a total lifetime of the battery of 20 years.

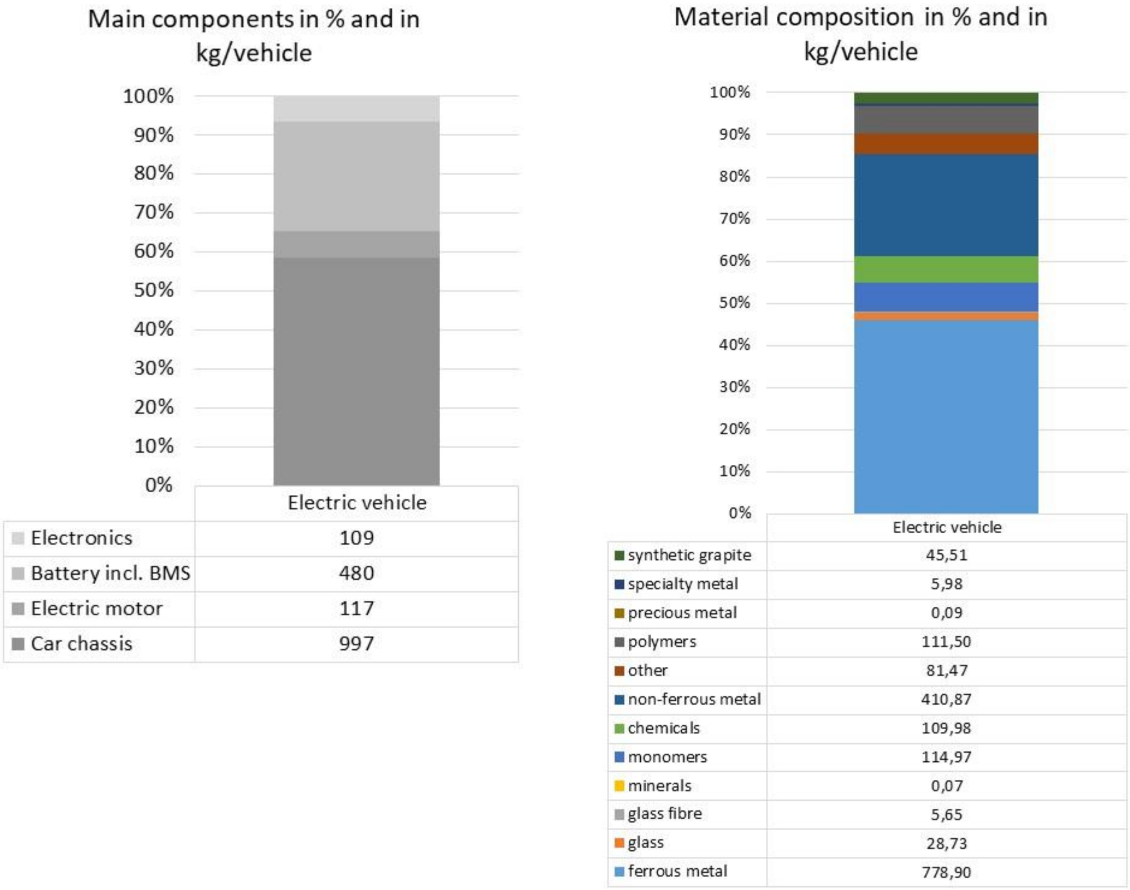
A typical composition of electric vehicles is shown in **Figure 11**including detailed composition of the sub-component battery and its typical material composition. Lithium-ion batteries consists of an outer case, cathode, anode, electrolyte, separator as well as Cu- and Al-electrode material.

Figure 11**: Illustration of the material composition of an electric vehicle**



Source: based on data from Hawkins (2013), Ellingsen (2014) and Hischier et al. (2007a); Hischier et al. (2007b), own compilation.

Figure 12: **Composition of main components and materials of an electric vehicle**



| | Electric vehicle |
|---|---|
| ■ Electronics | 109 |
| ■ Battery incl. BMS | 480 |
| ■ Electric motor | 117 |
| ■ Car chassis | 997 |

| | Electric vehicle |
|---|---|
| ■ synthetic grapite | 45,51 |
| ■ specialty metal | 5,98 |
| ■ precious metal | 0,09 |
| ■ polymers | 111,50 |
| ■ other | 81,47 |
| ■ non-ferrous metal | 410,87 |
| ■ chemicals | 109,98 |
| ■ monomers | 114,97 |
| ■ minerals | 0,07 |
| ■ glass fibre | 5,65 |
| ■ glass | 28,73 |
| ■ ferrous metal | 778,90 |

Source: based on data from Hawkins (2013), Ellingsen (2014) and Hischier et al. (2007a); Hischier et al. (2007b), own compilation.

## 7. Recycling Options

Polycrystalline silicon-based PV plants consist of more than 80% safety glass. The materials (e.g. silicon cells, front and back metallization paste) are bonded with very heat-resistant resins, which makes dismantling difficult and recycling only possible with great effort. The high glass content in PV plants is interesting for laminated glass recyclers. However, recycling is associated with contamination from glued cells and pastes containing heavy metals (Höller et al. 2016). Due to the currently small quantities of end-of-life PV plant, these impurities are currently still tolerated according to the "dilution principle" during the recycling of safety glass (mainly car windows and windowpanes). In the future, however, with increasing quantities, it is questionable whether these impurities can be used in laminated glass recycling. The proper disposal of components containing heavy metals is a critical aspect for many recyclers, which makes recycling more difficult. Such circumstances need to be analysed in more detail in further studies in order to subsequently be able to increase the recycling rates for PV plant.

A frequently used recycling option for safety glasses is in glass wool production (Höller et al. 2016, Stolz et al. 2017). Recycling technologies for silicon-based PV plants are based on physical demolition and separation, e.g. at the company Reiling und Exner Trenntechnik in Germany. They generate outputs such as bulk glass cullet, aluminium scrap and copper scrap (Stolz et al., 2017). Balance of system (BOS) components (e.g. mounting structure and electrical installations) are usually separated from the PV modules and sent for metal recycling (mounting, rails) or WEEE recycling (junction box, inverter, etc.) (Stolz et al. 2017). Semi-conductor materials made of silicon or precious metals such as silver are currently not recovered due to their relatively low mass fraction (Ardente et al. 2019). Recovery of such valuable metals could be achieved, for example, through hydro-metallurgical processes.

In summary, PV plants can be pretreated physically, thermally or chemically in order to separate the glass-solar cell composite (delamination). Furthermore, mechanical and/or chemical methods are used to post-treat the fractions obtained in order to be able to recover valuable industrial metals at the end by means of metallurgical processes (Fröhlich et al. 2017; Marwede et al. 2013).

High Efficiency Recycling of PV cells would be technically possible (e.g. to recover high quality glass, but also silicon), but is often hindered for economic reasons. Glass waste can be recycled to recover high purity, which is then suitable for medium to high quality applications, such as the production of flat glass. Silicon can be separated by acid leaching to obtain high-purity metallurgical silicon. Silver can be separated by electrolysis on graphite rods. Provided that plant capacity can be utilised and a market for secondary raw materials such as recycled silicon can be identified, highly efficient recycling would be feasible. Aluminium from frames and internal connectors can be dismantled by automated disassembly and further processed in high purity. Copper waste from cables and from internal parts of the PV panel can also be recycled (Ardente et al. 2019).

In the case of wind turbines, it should be mentioned that so far only a fraction of the existing turbines in Austria have been dismantled – according to Einsiedler (2017) only a total of 35 wind turbines by 2016. However, more dismantling is expected in the coming years due to repowering. The wind turbines dismantled in the course of repowering can still be used further and are therefore sold on the re-use market for wind turbines. Some companies have already specialised in the sale of used wind turbines (e.g. Green-Ener-Tech, Repowering Solutions, Enerpower, Windturbines). The second-hand wind turbines are cheaper and thus more affordable for emerging or developing countries. The advantage is that these countries benefit from technology transfer and can also gain a foothold in the field of renewable energy production. The shorter procurement time and the lower capital investment can reduce the financial risk, which can be crucial especially in economically and politically uncertain countries (Welstead et al. 2013). However, it can be assumed that the demand for old wind turbines will decrease with a stronger expansion of wind turbines.

Larger (e.g. 3 MW) turbines in particular are less attractive for further transport and thus for re-use than smaller turbines. In addition to being used as spare parts donors, they can then only be dismantled for recycling (Kaiser and Seitz 2014). This involves removing wiring, fluids, lubricants and coolants, decoupling the rotating union and then removing the rotor blades and hub with a crane. The nacelle and drive train are also dismantled. Steel towers are dismantled into their individual segments and can thus also be easily transported away and re-used. In the case of hybrid towers, the concrete segments must be separated from the steel structure. Depending on the agreement, the foundation is left in the ground or partially removed (topmost 1 to 2 m) to restore water permeability of the soil. As the foundation is made of reinforced concrete and therefore very durable, it can mostly remain on site, with disposal costs reduced and low environmental risks expected.

Since a wind turbine is composed of very high-mass and recyclable fractions of concrete, steel, copper and aluminium, a very high recycling rate of 80-90% can be achieved (Seiler et al. 2014). Mining is economically attractive because of the copper wiring in the generator. Concrete-steel structures can be broken into larger pieces and transported to construction waste recycling plants. Concrete can also be crushed using impact and jaw crushers and mixed into fresh concrete as concrete chippings, for example. Copper cables are separated into copper and plastic granulates by means of dry mechanical crushing in granulators and subsequent density separation. The recycling of steel, copper, aluminium and iron enables high-quality recovery of secondary raw materials used in the metal industry.

The situation is different with glass-fibre and carbon-fibre reinforced plastics (GFRP and CFRP) and epoxy resins, which are increasingly used in rotor blades and for which there are still hardly any commercial recycling methods. These materials are mostly subject to downcycling and are used in cement factories as processed substitute fuels for energy generation. However, it is expected that with an increase in the number of rotor blades to be disposed of, other recycling routes will have to be established, as co-incineration in cement factories can also be associated with problems in terms of incomplete burnout or the formation of harmful combustion products (e.g. aromatic hydrocarbons, hydrogen cyanide, carbon dioxide, carbon monoxide, etc.). Furthermore, halogenated flame retardants added to GFRP or CFRP can be unintentionally released by the combustion process and thus pass into the exhaust gas stream. Thus, persistent fibres can hinder the combustion process, increase the amount of fly ash and cause malfunctions in the incinerator (Beauson and Brøndsted 2016). During recycling, the GFRP and CFRP composites need to be separated into homogeneous particles, which can be done mechanically or chemically. However, both processes are currently not economically viable due to the higher costs of the secondary material compared to the primary raw material. In addition, the high energy input for comminution and the large quantities of chemical waste still speak against these processes. Therefore, other options for the use of discarded rotor blades are currently preferred. In Jensen and Skelton (2018), applications in bridge construction, for a structure in children's playgrounds, for indoor and outdoor furniture, and for durable shelters were highlighted. The main barriers to these potential applications are currently due to the availability of rotor blades and limitations in design or further processing. In this context, it is worth mentioning that in Austria, too, there have already been attempts to find innovative ideas for discarded rotor blades by means of competitions (e.g. Energie Burgenland competition for the re-use of old blades; Kurier, 10 May 2020).

In a research project published in Jensen and Skelton (2018), other mechanical and thermal recycling routes for rotor blades were also tested (e.g. chipboard with shredded GRP or GRP dust used for wood coating). Apart from energy-intensive processing steps, these applications also lead to further problem areas in its recycling. Jensen and Skelton (2018) concludes that recovery of the materials for use in production is currently not possible. Good progress in extracting the fibres with good quality has been noted, but only on a laboratory scale with such high energy consumption and costs that cannot currently compete with the price of virgin material. For the present scenario of High Efficiency Recycling, a recycling rate of only 50% is therefore assumed.

Both a PV plant and a wind turbine contain electronic components such as capacitors, circuit boards, diodes, transformers, etc., which can be recycled via WEEE recovery. In addition to aluminium, steel and copper, these WEEE also contain precious and special metals such as tantalum. However, the recycling route tends to be copper metallurgy, which guarantees a high recycling yield for copper but not for tantalum (Luidold 2013). The recycling rate of critical metals, such as tantalum or platinum group metals, is currently still low and currently occurs more in the case of single-variety production waste or other special segments such as carbides. However, for a circular economy and for security of supply, it will be necessary to increase recycling efficiency. Therefore, in the High Efficiency Recycling scenario, gold, silver and tin are also expected to be recovered. The recycling potential of special metals such as indium, gallium, germanium and tantalum has not been cited, as current recycling rates are very low and mainly limited to production waste. The metal content in the products is relatively low. For example, the tantalum content of capacitors built into the inverter is about 0.005 g per installed Wp. Furthermore, there is currently still a lack of efficient recycling technologies to recover special metals such as rare earth metals (UNEP 2011). For these reasons, an estimate of the future recycling possibilities for these special metals could not be made. A summary of the metals and other recyclable materials considered for the individual scenarios is presented in **Fehler! Verweisquelle konnte nicht gefunden werden.**.

Table 3: **Summary of the recyclable materials considered for the individual scenarios, indicating the recycling rate (RR)**

| | Base Case Recycling (SR1) | High Efficiency Recycling (SR2) |
|---|---|---|
| Definition | Status quo, focus on mass-based recovery rate | Technically possible from today's perspective, Focus on material-related recovery rate |
| PV PLANT | | |
| Aluminium | RR 92%: Al frame is removed manually, equivalent to primary aluminium [1] | RR 94%: Al frame and Al from further joints (automatic separation and further processing), equivalent to primary aluminium [1] |
| Copper | RR 72%: Copper scrap from cables equivalent to primary copper [1] | RR 90%: from cables and other connections[1] |
| Glass | RR 9%: Glass scrap/wool; equivalent to low-quality applications[1] | RR 88%: Glass is separated by a highly selective process to achieve high purity. Antimony in the glass is lost [1] |
| Silicon | RR 0%[1] | RR 95%: Silicon separated by acid leaching to obtain high-purity silicon metal of metallurgical quality[1] |
| Silver | RR 0%[1] | RR 94%: Silver separated by electrolysis on graphite rods, equivalent to primary material[1] |
| Electronics | Only Al, Cu, Fe[2] | plus Au, Ag, Sn[2] |
| WIND TURBINE | | |
| Concrete | RR 92% from the foundations[3] | RR 92% from the foundations[3] |
| Steel | RR 92%[3] | RR 92%[3] |
| Aluminium | RR 92%[3] | RR 92%[3] |
| Copper | RR 95%[3] | RR 95%[3] |
| GFK/CFK | RR 0%[1] | RR 50%[1] |
| Electronics | only Al, Cu, Fe [2] | plus Au, Ag, Sn[2] |
| E-VEHICLES | | |
| Focus on battery recycling | RR 70% (on the example of Umicore)[4] | RR 80% (on the example of Retriev)[4] |

Source: [1]Ardente et al. (2019), [2] Own estimation, [3] Vestas (2017), [4] Nigl (2016).

If lithium-ion batteries are not properly collected and recycled at the end of their life it increases the risk of releasing hazardous substances and constitutes a waste of resources. Furthermore, the collection of batteries comes along with several risks (e.g. mechanical and thermal stress, overcharging, deep discharging, short circuits). Safety aspects need to be considered to avoid a thermal runaway.

From a resource point of view, metals such as cobalt, copper and nickel are interesting to extract (e.g. via ultra-high temperature; UHT process of Umicore) as well as lithium compounds. However, the diversity of the materials and the variety of the shapes and sizes of batteries used in electric vehicles is a challenge for the recycling (Huang et al. 2018). In general, spent lithium-ion batteries are first discharged and then dismantled to separate components, such as case, cables, screws. The cell recycling undergoes either hydrometallurgical or pyrometallurgical processing. Hydrometallurgical processes are the most used technology for battery recycling (e.g. Retriev Technologies Inc. in Canada). A high recover rate of metals can be achieved by this method. The downside of this process is though, that large amounts of acid and auxiliary agents are needed, which requires a recycling of the waste sludge produced in this process.

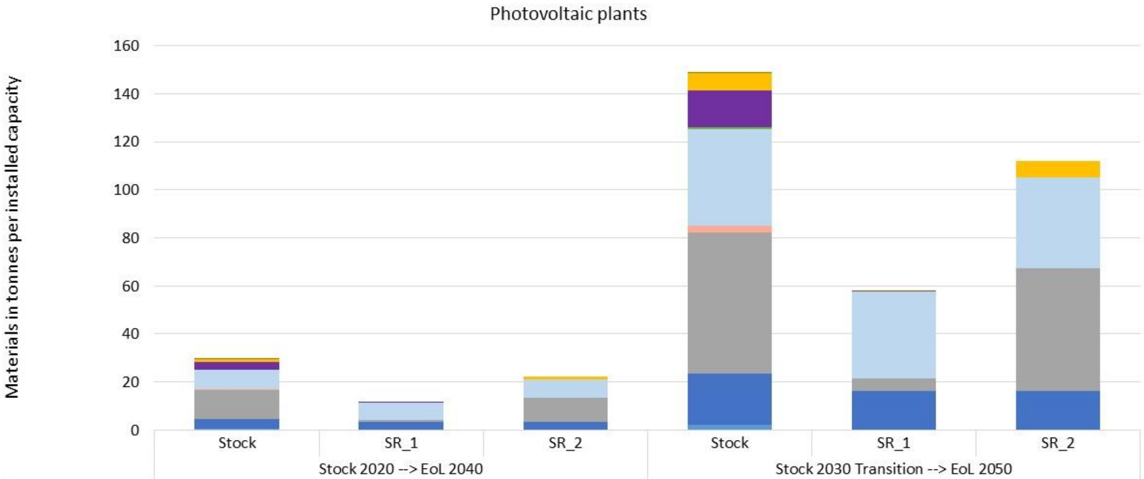
Pyrometallurgical processing is commercially used at e.g. Umicore (Belgium). In the process mainly Co and Ni are recovered from spent lithium-ion batteries. At Batrec Industrie AG (Switzerland) a direct physical recycling process is used for lithium-ion batteries LIB, which result in outputs such as non-iron metals, nickel-iron, electrode materials and plastics (Nigl 2016). The determining factor for a profitable recycling process is at the moment cobalt.

The strongly increasing amount of end-of-life batteries will become a challenging material stream for the waste management sector in Austria (Nigl 2016). Challenges and threats to lithium-ion battery recycling were identified in Huang et al. (2018) and in Beigl et al. (2021). Firstly, technology and chemistry of lithium-ion batteries are ever-evolving, leaving the recycling technologies behind. Furthermore, if cathodes will be fabricated with cobalt-free materials, the economic efficiency of the pyrometallurgical process is questionable. Another threat is that lithium-ion batteries and lead-acid batteries may be designed geometrically equivalent in order to be interchangeable for some appliances (e.g. electric bicycles, mini-sized electric vehicles), which may lead to improper disposal as the user cannot identify and sort accordingly. Another major concern are safety and risk issues during collection and storage of spent lithium-ion batteries. Mechanical or thermal stress, overcharging, deep discharging, internal or external short circuit can cause thermal runaway, which leads to explosions and/or fires. The handling of spent lithium-ion batteries has earned increased attention due to increasing fire events at waste management facilities or transport vehicles in Austria. Requirements on a safe collection and storage became stringent and have been fixed in national directives (e.g. in Austria, Abfallbehandlungspflichtenverordnung (BGBl. II Nr. 102/2017)).

## 8. Potential Amounts of Secondary Resources

The quantitative potential of secondary resources is presented for two timesteps: recycling of the plants installed in 2020 until 2040 and recycling of the plants installed in 2030 until 2050 according to the PEW volumes of the Transition scenario. The secondary resources in the Base Case Recycling scenario are referred to as SR1 and in the High Efficiency Recycling scenario as SR2. **Figure 13** shows that in the case of a strong PV plant expansion rate (Transition scenarios), the secondary resource potential in 2040 in the Base Case Recycling is about 12-16 tons for ferrous and 28-36 tons for non-ferrous metals, as well as 4-5 tons for glass. In the case of High Efficiency Recycling, the amount of recovered glass could even rise to 40-51 tons. The yield of secondary silicon would be 5-7 tons. There would also be a potential to recover 60-80 kg of precious metals, such as gold and silver. Furthermore, with an installed quantity of polymers of 12-15 tons, possible ways for material recycling can also be established (e.g. plastic housings that can be easily dismantled; chemical recycling of rotor blades, etc.).

Figure 13: **Determined secondary resource potential in tons of the annually installed quantity of PV plants in Austria**

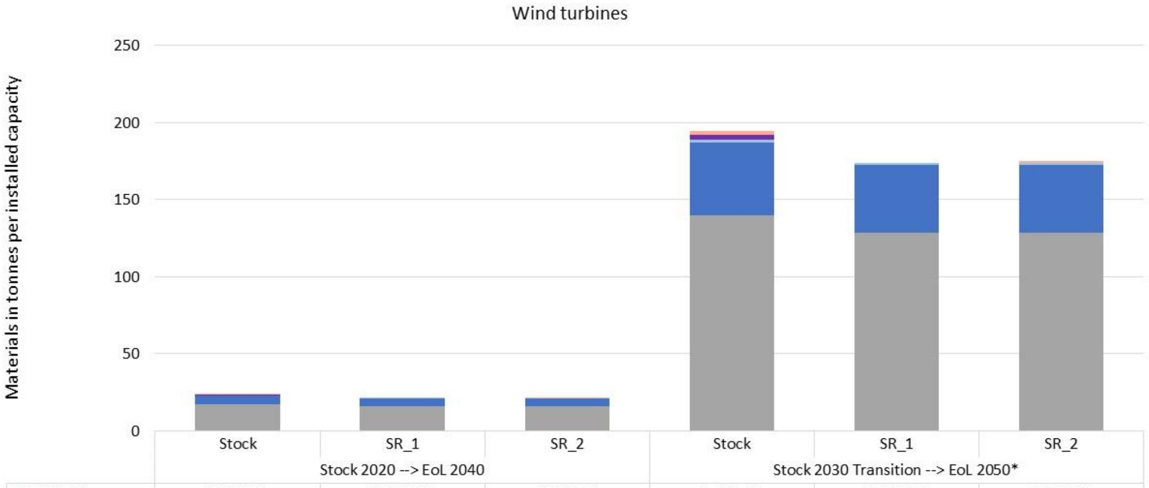


| | Stock | SR_1 | SR_2 | Stock | SR_1 | SR_2 |
|---|---|---|---|---|---|---|
| | Stock 2020 --> EoL 2040 | | | Stock 2030 Transition --> EoL 2050 | | |
| specialty metal | 3,15E-03 | 0,00E+00 | 0,00E+00 | 1,58E-02 | 0,00E+00 | 0,00E+00 |
| silicon | 1,41E+00 | 0,00E+00 | 1,34E+00 | 7,06E+00 | 0,00E+00 | 6,70E+00 |
| precious metal | 1,64E-02 | 1,35E-05 | 1,54E-02 | 8,20E-02 | 6,76E-05 | 7,70E-02 |
| polymers | 3,06E+00 | 7,85E-05 | 7,85E-05 | 1,53E+01 | 3,93E-04 | 3,93E-04 |
| other | 1,31E-01 | 1,50E-05 | 2,70E-05 | 6,53E-01 | 7,51E-05 | 1,35E-04 |
| non-ferrous metal | 8,07E+00 | 7,26E+00 | 7,55E+00 | 4,04E+01 | 3,63E+01 | 3,78E+01 |
| monomers | 5,89E-01 | 0,00E+00 | 0,00E+00 | 2,95E+00 | 0,00E+00 | 0,00E+00 |
| glass | 1,17E+01 | 1,05E+00 | 1,03E+01 | 5,86E+01 | 5,26E+00 | 5,14E+01 |
| ferrous metal | 4,30E+00 | 3,21E+00 | 3,21E+00 | 2,15E+01 | 1,61E+01 | 1,61E+01 |
| chemical | 3,84E-01 | 0,00E+00 | 0,00E+00 | 1,92E+00 | 0,00E+00 | 0,00E+00 |

Source: Own compilation.

Figure 14 shows that volume-wise most recyclable materials from wind turbines can be expected in the area of concrete, which can be mixed into fresh concrete or used in road construction. A large proportion of secondary resources can also be expected in the area of ferrous metals, especially low-alloy steel, but also cast iron. In the Transition scenario ferrous metals are expected to increase by 43.7 tons. Since no difference was made between Base Case Recycling (SR_1) and High Efficiency Recycling (SR_2) with regard to the recycling rate of concrete and ferrous metals, there are no differences here. The situation is different for precious metals, where between 9 g and 55 g can be expected in the High Efficiency Recycling scenario – 92 mass-% of which is silver. The recycling of magnets (here in the group of special metals) with 3 kg or 17.4 kg annually depending on the rate of expansion is uncertain. Magnets consisting of rare earths such as neodymium and dysprosium are needed in devices in the tower. The role of CFRP or GFRP is shown with an assumed recycling rate of 50% with a quantity of 223 kg to 1,300 kg for the year 2050.

Figure 14: **Determined secondary resource potential in tons of the annually installed quantity of wind turbines in Austria**

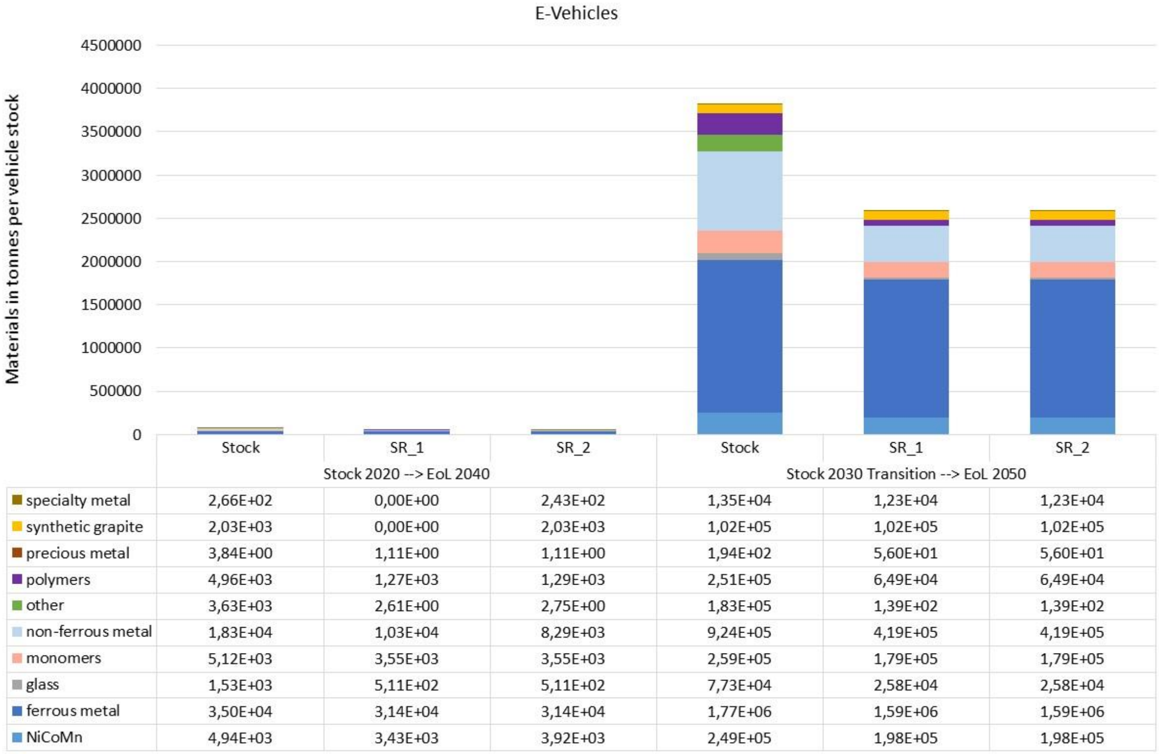


| | Stock | SR_1 | SR_2 | Stock | SR_1 | SR_2 |
|---|---|---|---|---|---|---|
| | | Stock 2020 --> EoL 2040 | | | Stock 2030 Transition --> EoL 2050* | |
| ■ CFK/GFK | 3,16E-01 | 0,00E+00 | 1,58E-01 | 2,60E+00 | 0,00E+00 | 1,30E+00 |
| ■ specialty metal | 2,12E-03 | 0,00E+00 | 0,00E+00 | 1,74E-02 | 0,00E+00 | 0,00E+00 |
| ■ precious metal | 7,40E-06 | 0,00E+00 | 6,66E-06 | 6,08E-05 | 0,00E+00 | 5,47E-05 |
| ■ polymers | 3,74E-01 | 0,00E+00 | 0,00E+00 | 3,07E+00 | 0,00E+00 | 0,00E+00 |
| ■ other | 4,33E-02 | 0,00E+00 | 0,00E+00 | 3,56E-01 | 0,00E+00 | 0,00E+00 |
| ■ non-ferrous metal | 1,90E-01 | 1,75E-01 | 1,76E-01 | 1,56E+00 | 1,44E+00 | 1,45E+00 |
| ■ monomers | 1,87E-04 | 0,00E+00 | 0,00E+00 | 1,54E-03 | 0,00E+00 | 0,00E+00 |
| ■ ferrous metal | 5,78E+00 | 5,32E+00 | 5,32E+00 | 4,75E+01 | 4,37E+01 | 4,37E+01 |
| ■ elastomere | 5,39E-05 | 0,00E+00 | 0,00E+00 | 4,43E-04 | 0,00E+00 | 0,00E+00 |
| ■ concrete | 1,70E+01 | 1,56E+01 | 1,56E+01 | 1,40E+02 | 1,28E+02 | 1,28E+02 |

Source: Own compilation.

**Figure 15** shows that most recyclable materials derive from ferrous (mostly low-alloyed or chromium steel) and non-ferrous metals (mostly Al, Cu) which is largely contained in the car chassis but also in the electronics, electric motor, and battery. Precious metals such as silver and gold can be derived from electronics and the electric motor. The electric motor furthermore contains specialty metal such as neodymium. There is no difference between Base Case Recycling and High Efficiency Recycling visible as the black mass of the battery recycling is containing low quantitative output amounts. Also, no difference with regard to precious or specialty metals are visible in the case of e-vehicles, as the recycling scenario focus only on battery recycling.

Figure 15: **Determined secondary resource potential in tons of the e-vehicle stock in Austria from 2020 and 2030**



| | Stock | SR_1 | SR_2 | Stock | SR_1 | SR_2 |
|---|---|---|---|---|---|---|
| | Stock 2020 --> EoL 2040 | | | Stock 2030 Transition --> EoL 2050 | | |
| ■ specialty metal | 2,66E+02 | 0,00E+00 | 2,43E+02 | 1,35E+04 | 1,23E+04 | 1,23E+04 |
| ■ synthetic grapite | 2,03E+03 | 0,00E+00 | 2,03E+03 | 1,02E+05 | 1,02E+05 | 1,02E+05 |
| ■ precious metal | 3,84E+00 | 1,11E+00 | 1,11E+00 | 1,94E+02 | 5,60E+01 | 5,60E+01 |
| ■ polymers | 4,96E+03 | 1,27E+03 | 1,29E+03 | 2,51E+05 | 6,49E+04 | 6,49E+04 |
| ■ other | 3,63E+03 | 2,61E+00 | 2,75E+00 | 1,83E+05 | 1,39E+02 | 1,39E+02 |
| ■ non-ferrous metal | 1,83E+04 | 1,03E+04 | 8,29E+03 | 9,24E+05 | 4,19E+05 | 4,19E+05 |
| ■ monomers | 5,12E+03 | 3,55E+03 | 3,55E+03 | 2,59E+05 | 1,79E+05 | 1,79E+05 |
| ■ glass | 1,53E+03 | 5,11E+02 | 5,11E+02 | 7,73E+04 | 2,58E+04 | 2,58E+04 |
| ■ ferrous metal | 3,50E+04 | 3,14E+04 | 3,14E+04 | 1,77E+06 | 1,59E+06 | 1,59E+06 |
| ■ NiCoMn | 4,94E+03 | 3,43E+03 | 3,92E+03 | 2,49E+05 | 1,98E+05 | 1,98E+05 |

Source: Own compilation.

## 9. Economic Impact Assessment

The economic impact assessment comprises two parts. First (**section 9.1**), the investment in recycling facilities from a microeconomic perspective is analyzed by using a discounted cash flow analysis that calculates the Net Present Value (NPV) of stylized facilities. This approach provides information on whether such a recycling process can be profitable – at given output prices for recovered materials - or whether it needs financial support. In the second part of the chapter (**9.2**), the cost information of the stylized facilities is combined with assumed EoL material flows from depreciated PEW installations according to the Transition scenario for the time span 2020 to 2050. The necessary investments to build up the waste treatment capacities and the accompanied operation of the facilities is integrated into the macroeconomic model, and impacts on GDP and employment effects in the Austrian economy are presented (**9.3**).

### 9.1 Microeconomic Perspective of Recycling Facilities

The microeconomic perspective analyzes the costs and revenues of single stylized recycling facilities to derive the NPV of an investment in this facility. This NPV shows whether an investment is profitable under given circumstances. Relevant inputs for this analysis are investment and operation costs that have been presented in **Table 2**, the recovery rates of the materials from the EoL and the selling prices of the recovered materials in the following **Table 4**.

Table 4: **Recovery rates and material prices for 2020 in % of total weight**

| | Basic Recycling | | | High Efficiency Recycling | | | |
|---|---|---|---|---|---|---|---|
| | Electric Vehicle | PV panel | Wind Power Plant | Electric Vehicle | PV panel | Wind Power Plant | Material Prices |
| | | % | | | % | | €/t |
| Glass scrap | 0.0 | 3.5 | - | 0.5 | 34.6 | - | 76 |
| Aluminium (Al) scrap | 1.5 | 22.6 | 0.0 | 6.0 | 23.1 | 0.3 | 1,038 |
| Copper (Cu) scrap | 0.6 | 1.8 | 0.0 | 2.5 | 2.2 | 0.2 | 3,665 |
| Steel scrap | 7.2 | 10.8 | 1.9 | 28.1 | 10.8 | 13.4 | 700 |
| Gold (Au) | 0.0 | 0.0 | - | 0.0 | 0.0 | 0.0 | 50,337,923 |
| Silver (Ag) | 0.0 | - | - | 0.0 | 0.1 | 0.0 | 583,966 |
| Silicone (proxy Ferrosilicone) | - | - | - | - | 4.5 | - | 1,480 |
| Manganese (Mn) | 0.1 | - | - | 0.6 | - | - | 1,500 |
| Nickel (Ni) | 0.1 | - | - | 0.3 | - | - | 12,194 |
| Lithium hexafluorphophate (LFP) | - | - | - | 0.2 | - | - | 200 |
| Cobalt (Co) | 0.0 | - | - | 0.1 | - | - | 28,900 |
| Cadmium (Cd) | - | - | - | - | - | - | 2,014 |
| Gallium (Ga) | - | - | - | - | - | - | 228,580 |
| Indium (In) | - | - | - | - | - | - | 97,410 |
| Molybdenum (Mo) | - | - | - | - | - | - | 18,386 |
| Tellurium (Te) | - | - | - | - | - | - | 63,494 |
| Tin scrap (Sn) | - | 0.1 | - | - | 0.1 | 0.0 | 11,738 |
| Selenium (Se) | - | - | - | - | - | - | 21,588 |
| Zinc (Zn) | - | 0.0 | - | - | 0.0 | - | 2,189 |
| Plastics | - | - | - | - | - | - | 90 |
| Electronic Scrap / Junction box | 0.4 | 4.4 | 0.0 | 1.6 | 4.6 | 0.3 | 300 |
| NiCoMn 111 hydroxide | - | - | - | - | - | - | 800 |
| Waste treatment/disposal; Residuals | 90.0 | 56.8 | 91.4 | 60.2 | 20.0 | 39.6 | -150 |
| Hazardous Waste treatment/disposal | - | - | - | - | - | - | -500 |
| Waste (concrete) | - | - | 6.6 | - | - | 46.2 | 0 |
| **Total** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | **100.0** | |

Source: Own compilation.

The recovery rates are a product of this project and the detailed data set is provided in **Annex Tables A1-5**. Here **Table 4** summarizes the composition of recoverable materials per tons EoL EV, PV and wind power plant which is equal to an output share for each recovery rate, Basic Recycling and High Efficiency. In the latter case, the recovery rates are substantially higher. We assume that all non-recovered materials need to be disposed. Since in the case of Basic Recycling of EV only 10% of the vehicle's weight is recycled, 90% need to be disposed at a disposal cost rate of 150 €/t. The prices are identical to the prices in Table **1**. The multiplication of the recovered materials and the prices results in revenues per ton processed EoL (**Table 5**).

Table 5: **Revenues from recovered materials per tons of EoL input, 2020 prices**

| | Basic Recycling | | | High Efficiency Recycling | | |
|---|---|---|---|---|---|---|
| | Electric Vehicle | PV panel | Wind Power Plant | Electric Vehicle | PV panel | Wind Power Plant |
| | €/ton EoL | | | | | |
| Glass scrap | 0 | 3 | – | 0 | 26 | – |
| Aluminium (Al) scrap | 16 | 235 | 1 | 63 | 240 | 4 |
| Copper (Cu) scrap | 24 | 65 | 1 | 92 | 81 | 7 |
| Steel scrap | 51 | 75 | 13 | 197 | 75 | 94 |
| Gold (Au) | 5 | 23 | – | 20 | 138 | 1 |
| Silver (Ag) | 1 | – | – | 6 | 301 | 0 |
| Silicone (proxy Ferrosilicone) | – | – | – | – | 67 | – |
| Manganese (Mn) | 2 | – | – | 8 | – | – |
| Nickel (Ni) | 9 | – | – | 38 | – | – |
| Lithium hexafluorphosphate (LFP) | – | – | – | 0 | – | – |
| Cobalt (Co) | 7 | – | – | 30 | – | – |
| Cadmium (Cd) | – | – | – | – | – | – |
| Gallium (Ga) | – | – | – | – | – | – |
| Indium (In) | – | – | – | – | – | – |
| Molybdenum (Mo) | – | – | – | – | – | – |
| Tellurium (Te) | – | – | – | – | – | – |
| Tin scrap (Sn) | – | 7 | – | – | 7 | 0 |
| Selenium (Se) | – | – | – | – | – | – |
| Zinc (Zn) | – | 0 | – | – | 0 | – |
| Plastics | – | – | – | – | – | – |
| Electronic Scrap/Junction box | 1 | 13 | 0 | 5 | 14 | 1 |
| NiCoMn 111 hydroxide | – | – | – | – | – | – |
| Waste treatment/disposal | –135 | –85 | –137 | –90 | –30 | –59 |
| Hazardous Waste treatment/disposal | – | – | – | – | – | – |
| **Total Material Revenues** | **–20** | **337** | **–122** | **369** | **920** | **46** |
| Total Costs | –226 | –407 | | –366 | –1,111 | |
| **Profits** | **–245** | **–70** | | **3** | **–191** | |

Source: Own compilation.

**Table 5** resembles the value of the recovered material of PV and EV for the Base and High Efficiency case. The value of recovered material from electric vehicles, at the base recovery rate is negative – due to the assumed necessity to dispose unrecovered materials. This even leads to a negative revenue of the recovered materials. The same goes for wind power plants in the Basic Recycling case. In the other cases the value of the recovered material is positive. Per tons PV system (module, BOS, etc.) materials are worth 337 €/t or even 920 €/t can be extracted at 2020 prices. Also, the value of the recovered material per tons EV is positive in the High Efficiency case (369 €/t), mainly due to the extracted steel scrap.

Below the total revenues in **Table 5**, the capital and processing costs (**Table 2**) per tons are calculated. The revenues minus the costs result in potential profits of the recycling process per tons of EoL material flow. **Table 5** displays, that only in the case of EV recycling in the High Efficiency scenario, the investments are slightly profitable under the set conditions - prices and costs. The other recycling processes lead to negative profits between 66 and 245 €/t.

To calculate the NPV the cashflows over several years needs to be analyzed. The typical time span is 10 years according to D'Adamo et al. (2017). Fehler! Verweisquelle konnte nicht gefunden werden. summarizes the cash flows and resulting NPV based on the presented costs, rates and prices as well as a 5% discount rate. Cash inflow comprises recovered materials multiplied by material prices and facility capacity. Cash outflow summarizes annualized investment costs, operation costs, taxes on revenues (assumed 25%) and waste treatment costs. The resulting NPV of the four projects is shown at the very right in **Table 6**. The NPV of three of the facilities is negative. Only EV recycling in the High Efficiency case is profitable, which is mainly due to the recovery of steel. These results are in line with the findings of D'Adamo et al. (2017) for PV (0.84 €/kg PV module) and Thies et al. (2018) ("gate fee" of 0.24 €/kg) for LIB.

Table 6: **Net Present Value calculation for EV and PV recycling facilities in Base and High Efficiency scenario**

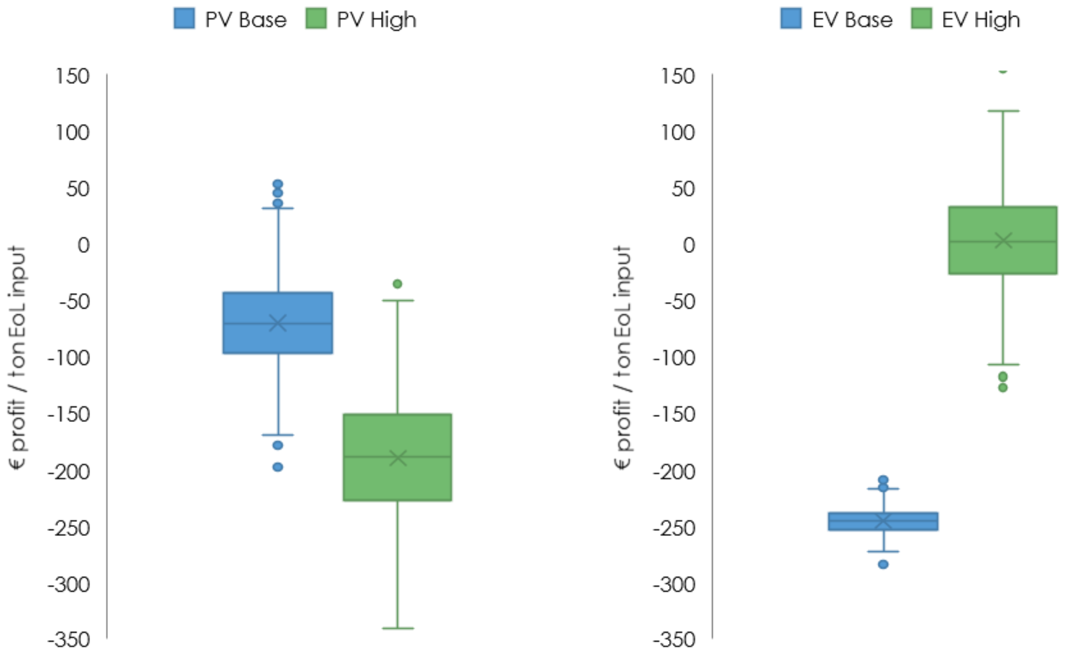
| | | y1 | y2 | y3 | y4 | y5 | y6 | y7 | y8 | y9 | y10 | y1-10 | NPV |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | In million € | | | | | | € per kg |
| **EV Base**<br>Capacity:<br>6,000 t/a | | | | | | | | | | | | | |
| | Cashflow in | –0.7 | –0.7 | –0.6 | –0.6 | –0.6 | –0.5 | –0.5 | –0.5 | –0.5 | –0.4 | **–5.59** | |
| | Cashflow out | –8.0 | –7.6 | –7.2 | –6.9 | –6.5 | –6.2 | –5.9 | –5.7 | –5.4 | –5.1 | **–64.53** | |
| | **Total** | **–8.65** | **–8.24** | **–7.84** | **–7.47** | **–7.12** | **–6.78** | **–6.45** | **–6.15** | **–5.85** | **–5.57** | **–70.12** | **–11.69** |
| **EV High**<br>Cap.: 6,000 t/a | | | | | | | | | | | | | |
| | Cashflow in | 13.01 | 12.39 | 11.80 | 11.24 | 10.70 | 10.19 | 9.71 | 9.24 | 8.80 | 8.38 | **105.46** | |
| | Cashflow out | –12.89 | –12.27 | –11.69 | –11.13 | –10.60 | –10.10 | –9.62 | –9.16 | –8.72 | –8.31 | **–104.47** | |
| | **Total** | **0.12** | **0.12** | **0.11** | **0.10** | **0.10** | **0.10** | **0.09** | **0.09** | **0.08** | **0.08** | **0.98** | **0.16** |
| **PV Base**<br>Cap.: 2,000 t/a | | | | | | | | | | | | | |
| | Cashflow in | 1.08 | 1.03 | 0.98 | 0.93 | 0.89 | 0.85 | 0.81 | 0.77 | 0.73 | 0.70 | **8.75** | |
| | Cashflow out | –1.30 | –1.24 | –1.18 | –1.13 | –1.07 | –1.02 | –0.97 | –0.93 | –0.88 | –0.84 | **–10.58** | |
| | **Total** | **–0.23** | **–0.21** | **–0.20** | **–0.19** | **–0.19** | **–0.18** | **–0.17** | **–0.16** | **–0.15** | **–0.15** | **–1.83** | **–0.91** |
| **PV High**<br>Cap.: 2,000 t/a | | | | | | | | | | | | | |
| | Cashflow in | 3.0 | 2.8 | 2.7 | 2.5 | 2.4 | 2.3 | 2.2 | 2.1 | 2.0 | 1.9 | **23.92** | |
| | Cashflow out | –3.6 | –3.4 | –3.2 | –3.1 | –2.9 | –2.8 | –2.7 | –2.5 | –2.4 | –2.3 | **–28.89** | |
| | **Total** | **–0.61** | **–0.58** | **–0.56** | **–0.53** | **–0.50** | **–0.48** | **–0.46** | **–0.44** | **–0.41** | **–0.40** | **–4.97** | **–2.48** |

Source: Own compilation.

## 9.2 Analysis of Price Variations

A large part of the recovered materials are scrap metals. The prices for scrap metals tend to develop like the prices of their primary counterparts as, for instance, the price for steel and steel scrap[3]. Hence, the prices of the output materials underly a range of fluctuations. In this analysis we try to estimate how strong fluctuations in material prices can influence the profitability of our four recycling facilities. Therefore, we applied a range of 1,000 price variations[4] (Gaussian distribution) of the material prices and their respective standard deviation (Table **1**) and calculated the respective profit per tons of EoL material stream. The average value in Fehler! Verweisquelle konnte nicht gefunden werden.**Figure 16** is equal to the profit per tons in **Table 5**.

Figure 16: **Profits of recycling facilities by varying output prices**



Source: Own compilation.

The analysis shows, that despite partly strong variations of prices, the inner two quartiles (i.e. 50% of the cases) stay negative for the recycling of PV (both cases) and for EV in the Base Recyling case. In the latter, the variation is quite small due to the large share of unrecovered waste in this variant and the assumption that disposal costs do not vary.

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[3] Price for steel see World Bank (2021) Pinksheet; price for steel scrap in international trade investigated in UN database COMTRADE (2021).

[4] This approach resembles an "one-dimension Latin Hypercube sampling" where the distribution of each node is normally distributed and not random.

## 9.3 Macroeconomic Effects

The macroeconomic perspective is quite different to the microeconomic one. Expenditures or costs are not necessarily negative because they can cause domestic production activities and thereby generate value-added and employment.

In this analysis we focus on the economic impact of the domestic treatment of EoL waste flows in the time span from 2020 to 2050 in accordance to the Transition scenario. We derive necessary investment volumes and operation expenses required to treat these material flows based on the derived costs and capacities (**sections 4.4 and 4.5**). Based on the recovery rates and the prices for the materials profits, the output value of the recycling facility can be derived. The NPV analysis (**section 9.1**) provides information on the magnitude of a potential "gate fee" that assures investments into these recycling facilities are profitable and will take place. This information is processed with the WIFO.DYNK model. In the model an artificial sector is designed that resembles the economic activity (investments and operation) of stylized recycling facilities. The output of the artificial sector (= secondary resources) is fully exported. This is not necessarily realistic since Austria's industry is already using scrap materials such as steel and aluminum scrap. But from a macroeconomic perspective the export of a ton of scrap has the same GDP impact as the avoidance of a ton of imported scrap. Therefore, this simplifying approach can be applied. The "gate fee" is paid by private households and is implemented as a direct subsidy of the artificial sector and thus represents a viable policy instrument to spur recycling activities. The implementation of a "gate fee" has a compensating negative impact on the GDP because these expenses decrease the household consumption.

Table 7: **EoL waste flows, 2020-2050**

| | Electric Vehicles | | | Photovoltaic Panel | | | Wind Power Plant | | |
|---|---|---|---|---|---|---|---|---|---|
| | LIB cells | LIB BMS & Cooling | Vehicle | Module | Mounting | BOS | Turbine | Tower | Foundation |
| | | | | | 1,000 tons | | | | |
| 2015 | - | - | - | - | - | - | - | - | - |
| 2020 | - | - | - | - | - | - | - | - | - |
| 2025 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2030 | 7 | 1 | 35 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2035 | 43 | 6 | 204 | 3 | 1 | 1 | 3 | 13 | 48 |
| 2040 | 99 | 13 | 471 | 47 | 16 | 12 | 8 | 42 | 153 |
| 2045 | 137 | 18 | 651 | 115 | 40 | 29 | 9 | 49 | 179 |
| 2050 | 133 | 17 | 629 | 127 | 44 | 32 | 20 | 104 | 378 |

Source: Own compilation.

Regarding the EoL waste streams, Fehler! Verweisquelle konnte nicht gefunden werden. summarizes the possible flows in the time span until 2050, assuming the massive expansion of renewable energy in the Transition Scenario. According to that scenario and assumed lifetime[5], around 130,000 tons of EoL LIB and PV modules can occur in the mid 2040s.

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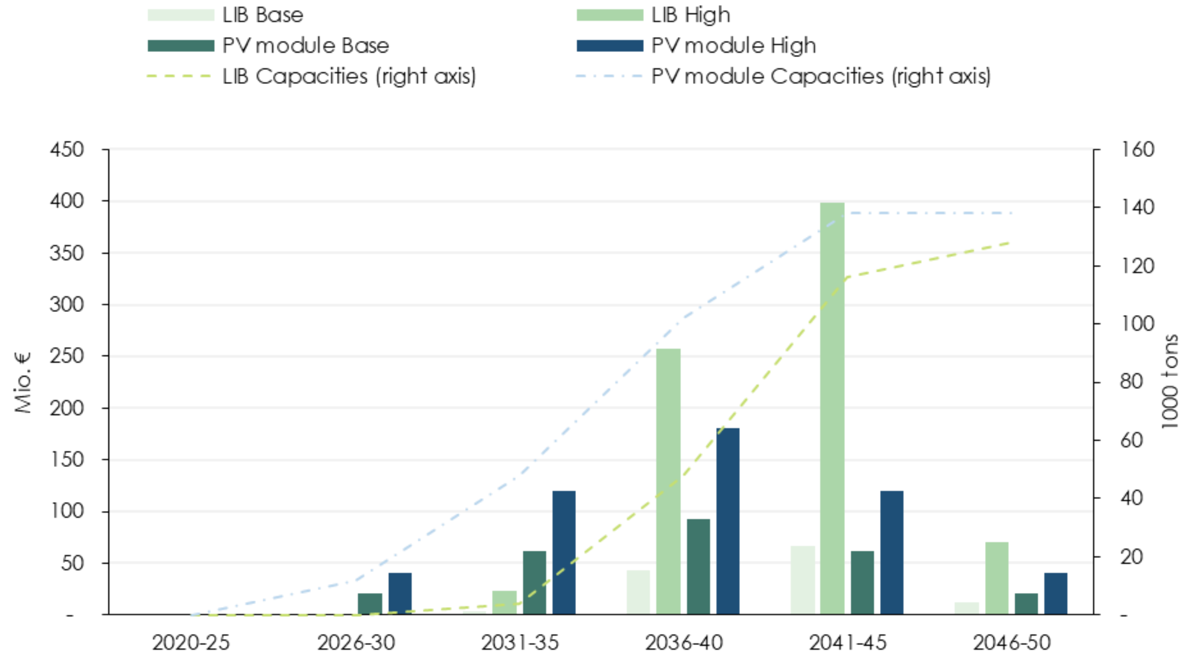
[5] PV 20 years (std.dev 3); EV-LIB 11 years (std.dev. 3); Wind Power Plant 15 years (std.dev.2)

The calculation of the required investments is set in a way, that there has to be enough capacity to be able to process the upcoming EoL waste flows. **Figure 17** summarizes the investment volume which increases with the upcoming EoL flows in the 2030s. In the time frame of five years (2041 to 2045) cumulative investments of around 400 million € need to be undertaken in the case of High Efficiency Recycling of the LIB. Due to lower investment costs (accompanied with lower recovery rates) in the Basic Recycling variant the volumes amount to 60 million € in the same time frame only. In both cases, LIB and PV module recycling, the treatment capacities increase to around 130,000 t/a.

Figure 17: **Investments in recycling facilities and the cumulated capacities**



Source: Own compilation.

The impact on GDP from recycling stems from several sources. Wages, salaries, taxes and profits generated by the recycling facilities resemble direct contributions to the GDP. The expenses during the production process are to some extend bought from domestic companies[6] and thereby cause positive impacts on the GDP in other up-stream sectors indirectly. The same holds for the necessary investments which demand domestic commodities and services to some extent. By "induced" effects we define the additional consumption of private households caused by additional incomes from direct and indirect effects. The "gate fee" in this simulation is assumed to be paid by the private households as a markup on electricity, electric cars and

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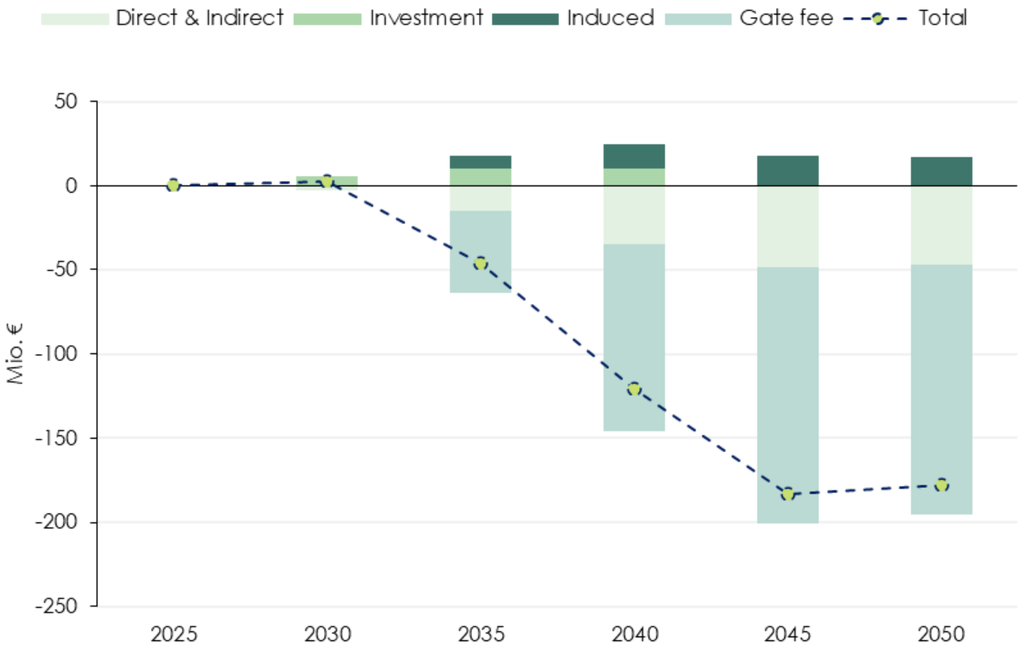
[6] The input structure of the recycling facilities with respect to variable and fixed costs is provided in the Annex, Tables A 1-5.

PV installations. This reduces the consumption of other services and commodities and has a compensating negative impact on the GDP.

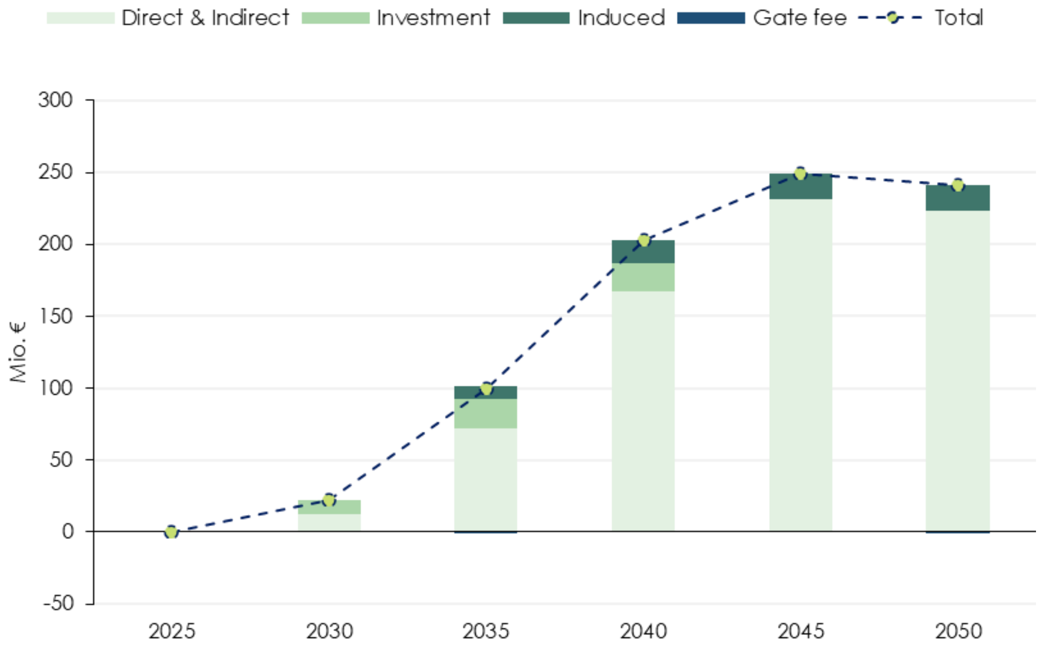
Figure 18: **GDP effects from recycling – LIB Basic Recycling**



Source: Own compilation.

The numeric results on the GDP impact as table can be found in the Annex, **Tables A 1-5**. **Figure 18** shows the decomposed impact on the GDP for the Base case of LIB recycling. As depicted in **Table 5**, this variant shows the worst profitability with a loss of 254 €/t LIB. This means that the economic impact of this economic activity has negative profits (negative surplus) under the set prices for secondary resources, and hence is an uneconomic process and contributes negatively to the GDP. The payment of the gate fee by the private households contributes an even higher negative impact due to the loss of domestic demand. Nevertheless, during the production process, wages are paid which have a slight positive impact since they are partly used for consumption. In these years where investments are necessary, they also contribute positively to the GDP. Most prominently in the 2030s and 2040s. The overall GDP impact is –180 million $€_{2020}$ which is about 0.03% of an assumed GDP of 600 billion € in 2050.

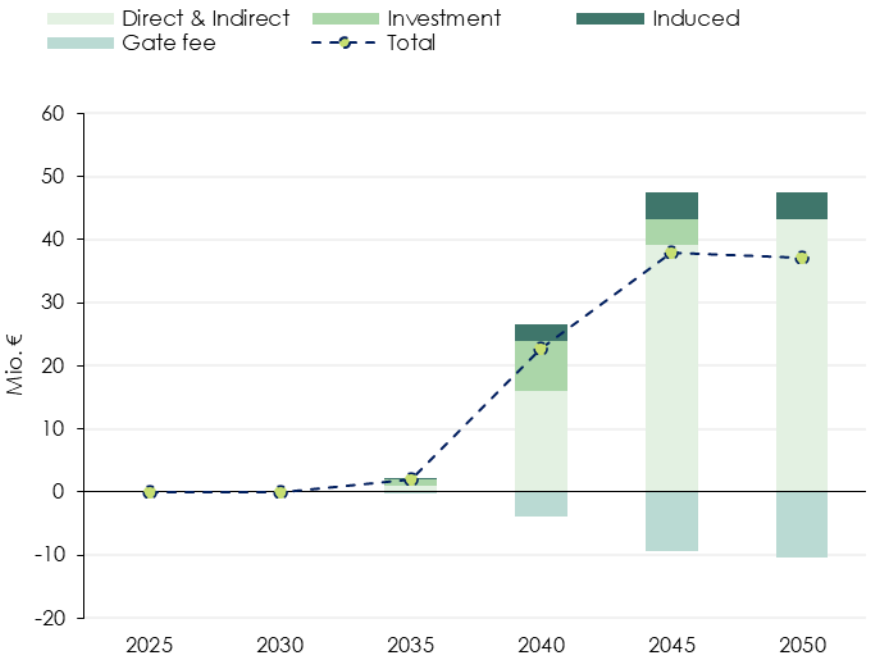
Figure 19: **GDP effects from recycling – LIB High Efficiency Recycling**



Source: Own compilation

The microeconomic profit per ton treated of LIB in the High Efficiency case is slightly positive (**Table 5**) which results in an overall positive effect on Austria's GDP (**Figure 19**). Only minor amounts of gate fees need to be paid, leading to substantial direct and indirect contributions to GDP. Hence the direct profits and wages of the process contribute to GDP as well as the upstream expenses. In the 2040s the contribution reaches about 250 Mio. €$_{2020}$ which equals to about 0.04% of 2050's GDP.

Figure 20: **GDP effects from recycling – PV modules Basic Recycling**



Source: Own compilation.

Even though the Basic Recycling variant of PV installations recycling shows a negative profit of 70€/t (**Table 5**) the overall impact of this process on GDP is positive if recycling is implemented under these conditions. The explanation is that taxes are part of the "costs" of a business. On the one hand, they reduce profits of the company, and, on the other hand, they are part of the value added that is taxed. In other words, both, the profits plus taxes represent the value added in this process. Since the value added is positive, the process is profitable from a macroeconomic point of view[7]. Nevertheless, a gate fee is implemented which has a negative consumption impact of about 10 million €. The overall GDP impact reaches almost 50 million €$_{2020}$ which is about 0.01% of the Austrian GDP in 2050.

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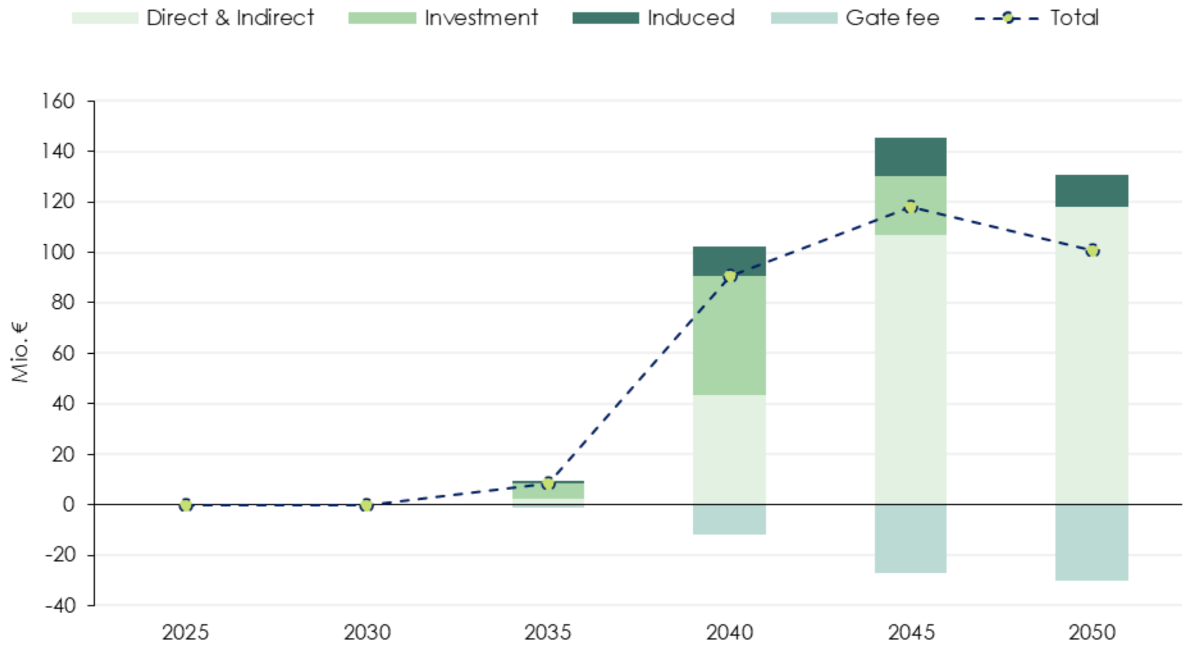
[7] See Annex A-i for Details of NPV calculations

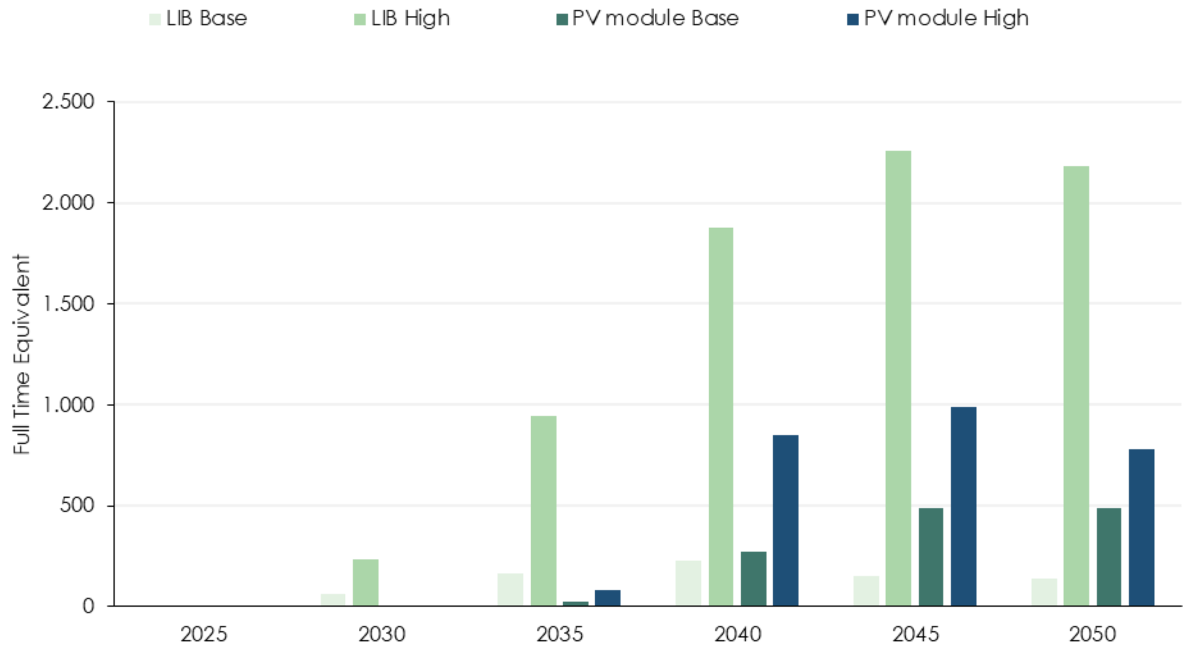
Figure 21: **GDP effects from recycling – PV modules High Efficiency Recycling**



Source: Own compilation.

The High Efficiency Recycling of PV shows quite high losses per treated ton (–191 €/t in **Table 5**). However, the GDP impact is positive. The explanation is similar to the Base case. Without the assumed taxation of profits, the process would be profitable under the given conditions. This results in a positive impact of GDP of around 120 million $€_{2020}$ or 0.02% of 2050's GDP.

Figure 22: **Employment effects from recycling LIB and PV modules**



Source: Own compilation.

Employment effects (**Figure 22**) are overall positive, even for the Basic Recycling" case. The reason for that is that the simulated facility is operating. From an investor's point of view, it may generate negative profits, but it nevertheless employs people and pays wages. This is a positive contribution to total employment. This and the positive employment impact from the up-stream expenses weight out the negative contribution of the gate fee payments. However, in the relatively high positive impact of the High Efficiency variant of LIB recycling on GDP resembles in employment of over 2,000 full time equivalents, around 0,07% of the 2020 level.

To summarize, the microeconomic analysis shows that the recycling of PV and electric vehicles is touching profitability depending on the technology applied and the amount of materials extracted. The selling price of the recovered materials is highly relevant but fluctuations as in the recent past would not transfer a process from non-profitable to profitable, at least if prices do not increase or decrease uniformly. From a macroeconomic perspective even a non-profitable recycling process can contribute positively to GDP due to the fact that some expenses stay in the domestic economy and multiplier effects increase the impact of economic activities.

## 10. Discussion

The method presented here for evaluating EoL recycling of PV plants and e-vehicles in Austria assumes four impact channels that influence domestic value creation. The first impact channel is the investment in recycling plants. This activity generates demand for capital goods that are produced in Austria and thus generate domestic employment and value added. The second impact channel is the operation of the plants. Here, goods, services and labor are used to produce the desired products. The provision of these goods and services is done, among others, by upstream domestic companies and thus indirect positive effects are initiated there. The remuneration of the workers in the recycling plant is not only part of the direct value added, but also the basis for the induced consumption effect since a part of these wages and salaries is used by private households for consumption purposes. The third impact channel is the revenue from the sale of the recovered materials, which are sold on the international market in this simulation. As the material flows of the plant operation are given, the revenues are strongly dependent on the international sales prices of resources. Revenues are used to cover costs (personnel, materials) on the one hand, and to repay investment loans (in the amount of depreciation) on the other. The difference between revenues and costs represents operating profits. Operating profits are part of direct value added and thus contribute directly to GDP. A further use of operating profits, for example for profit distributions or further investments, is not analyzed in this simulation. The fourth impact channel is disposal fees ("gate fees"). These are defined exogenously when the operation of recycling plants is not profitable due to the level of sales prices and are paid by renewable energy operators (here paid by private households for reasons of simplicity). This fee reduces disposable income, consumption and the associated value added in the economy and thus partly compensates for GDP value creation from recycling.

To define the amount of the disposal fee ("gate-fee"), the following analysis was applied. Since sales revenues depend on the prices for secondary materials on the international market, operating profits (as the difference between revenues and costs) are also determined by these prices. If material prices are high, this is reflected in high operating profits. If prices are low, however, operating profits are low or even negative. In the latter situation, an investment is unprofitable from a business perspective and would not be realized. To overcome this purely business point of view of unprofitable investments and - in this case - to valorize the other environmental-economic functions of recycling, such as provision of secondary raw materials and resource security, reduced GHG emissions and other positive environmental impacts, a disposal fee has been introduced as a policy instrument, which is to be paid by private households and accrues to the plant operators, so that the operation of the plant becomes profitable. The amount is set as to achieve at least a net present value of 0, i.e. the plants are just profitable, and recycling can be operated also from a microeconomic perspective.

The analysis shows, low (secondary) resource prices on international markets may be a barrier for implementing and operating recycling plants for renewable energy technologies. Consequently, public policies such as subsidizing investments, operation or implementing a disposal-fee ("gate fee") for recycling renewable energy technologies are required to generate non-market benefits from recycling such as climate mitigation, resource security, and treatment of

EoL waste streams. This constitutes a case of internalization of external effects from renewable energy deployment. In addition, national employment and value-added can be gained from establishing recycling loops for renewable energy technologies.

With respect to the macroeconomic effects from recycling of wind power plants, the analysis needs further research into different instances, i.e. regarding costs for recycling or disposal of different parts of the wind turbine, or, alternatively, regarding sales prices for re-use of wind turbines abroad. Today, it is common practice to export wind turbines close to their economic lifetime end to Eastern European countries, Asia or Africa. The sales prices for such export strategies needs further research and could not be assessed within the realm of the current framework.

This study focused on the GDP impact connected to the investment and operation of recycling facilities given the objectives of climate mitigation and resource efficiency. It showed that the positive net economic effects are possible given public incentives. The study did not attempt to analyze any opportunity costs of the investment in recycling facilities. The investment in such technologies and their public support remains a political and societal decision given the challenges of reaching net-zero GHG emissions by 2040.

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## Annex: Auxiliary Data

Table A 1: **Material prices**

| Material | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | Standard Deviation | Source |
|---|---|---|---|---|---|---|---|---|
| Steel | 2,368 | 1,850 | 1,922 | 1,759 | 1,752 | 2,430 | 15% | [6] |
| Pig Iron | 347 | 278 | 343 | 371 | 376 | 316 | 11% | [6] |
| Iron Ore | 51 | 56 | 65 | 58 | 84 | 96 | 26% | [5] |
| Steel scrap | 311 | 262 | 330 | 367 | 327 | 303 | 11% | [6] |
| Steel scrap |  |  |  |  |  | 700 |  | [1] |
| Copper | 5,029 | 4,455 | 5,457 | 5,626 | 5,438 | 5,402 | 8% | [6] |
| Copper | 5,075 | 4,677 | 5,612 | 5,432 | 5,397 | 5,460 | 6% | [5] |
| Copper scrap | 3,253 | 2,900 | 3,484 | 3,721 | 3,634 | 3,665 | 9% | [6] |
| Aluminium | 1,951 | 1,723 | 1,956 | 2,046 | 1,856 | 1,758 | 7% | [6] |
| Aluminium | 1,533 | 1,541 | 1,790 | 1,754 | 1,611 | 1,507 | 7% | [5] |
| Aluminium scrap | 1,260 | 1,118 | 1,298 | 1,316 | 1,156 | 1,038 | 9% | [6] |
| Tin | 15,451 | 15,674 | 17,225 | 16,527 | 17,076 | 15,342 | 5% | [6] |
| Tin | 14,798 | 17,230 | 18,247 | 16,759 | 16,757 | 15,146 | 8% | [5] |
| Tin scrap | 10,266 | 10,528 | 11,787 | 12,063 | 12,881 | 11,738 | 9% | [6] |
| Tin | 14,481 | 16,237 | 17,783 | 17,067 | 16,668 |  | 8% | [4] |
| Silver (Ag) | 465,520 | 529,640 | 499,064 | 420,300 | 468,194 | 583,966 | 12% | [5] |
| Gold (Au) | 34,369,550 | 38,579,603 | 36,774,638 | 33,948,392 | 40,200,782 | 50,337,923 | 15% | [5] |
| Nickel (Ni) | 10,926 | 9,219 | 9,468 | 10,910 | 12,494 | 12,194 | 12% | [5] |
| Glass scrap | 80 | 86 | 87 | 82 | 80 | 76 | 5% | [6] |
| Silicone  Primary form (Si) |  | 4,578 | 4,519 | 4,894 | 5,140 | 4,891 | 5% | [6] |
| Silicone  Primary form (Si) | 1,700 |  |  |  |  |  |  | [2] |
| Silicone (Ferrosilizium) | 1,098 | 1,134 | 1,148 | 935 | 1,284 | 1,480 | 16% | [4] |
| Mananese (Mn) | 1,600 | 1,500 | 1,600 | 1,900 | 1,600 | 1,500 | 9% | [4] |
| Indium (In) | 371,640 | 180,970 | 173,190 | 222,670 | 149,560 | 97,410 | 47% | [4] |
| Lithium Carbonat (LiC) |  |  | 20,500 | 15,000 | 8,800 | 5,400 | 54% | [7] |
| Lithium hexafluorphophate (LPF6) |  |  |  |  |  | 200 |  | [8] |

Table continued on the next page

| Material | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | Standard Deviation | Source |
|---|---|---|---|---|---|---|---|---|
| Cobalt (Co) | 26,900 | 24,000 | 36,400 | 60,900 | 47,300 | 28,900 | 38% | [7] |
| | | | | | | | | |
| Cadmium (Cd) | 1,240 | | | | | | | [3] |
| Cadmium (Cd) | | 1,208 | 1,581 | 2,558 | 2,261 | 2,014 | 28% | [9] |
| | | | | | | | | |
| Gallium (Ga) | 199,000 | | | | | | | [3] |
| Gallium (Ga) | 180,000 | | | | 129,274 | 228,580 | 28% | [7] |
| | | | | | | | | |
| Molybdenum (Mo) | 19,000 | | | | | | | [3] |
| Molybdän (Ferromolybdän) | 15,403 | 14,690 | 17,483 | 24,555 | 23,716 | | 24% | [4] |
| Molybdenum (Mo) | 21,000 | | | | | | | [10] |
| Molybdenum (Mo) | | | | | | 18,386 | | [7] |
| | | | | | | | | |
| Tellurium (Te) | 77,000 | | | | | | | [3] |
| Tellurium (Te) | | | | | 64,637 | 63,494 | 1% | [9] |
| Tellurium (Te) | 90,000 | | | | | | | [10] |
| | | | | | | | | |
| Selenium (Se) | 42,000 | | | | | | | [3] |
| Selenium (Se) | 30,194 | 16,695 | 36,178 | 32,083 | 19,134 | | 32% | [4] |
| Selenium Ignot (Se) | | | | | | 21,588 | | [11] |
| Zinc (Zn) | 1,741 | 1,888 | 2,561 | 2,476 | 2,276 | | 16% | [4] |
| Zinc (Zn) | 1,450 | | | | | | | [3] |
| Zinc (Zn) | | | | | | 2,189 | | [7] |
| | | | | | | | | |
| NiCoMn 111 / Black mass | | | | | | 800 | | [1] |
| | | | | | | | | |
| Plastics | | | | | | 90 | | [1] |
| Electro scrap | | | | | | 300 | | [1] |
| waste disposal | | | | | | 150 | | [1] |
| waste hazardous | | | | | | 500 | | [1] |

Sources:

| | |
|---|---|
| [1] | Thies et al. (2018), Table 15.4, Realistic Assumptions; |
| [2] | D'Adamo et al. 2017 |
| [3] | Cucchiella et al. 2015b |
| [4] | statista.de (2021a) |
| [5] | Worldbank (2021) |
| [6] | Comtrade (2021) |
| [7] | tradingeconomics.com (2021) |
| [8] | Alibaba.com (2021) |
| [9] | statista.de (2021b) |
| [10] | Cucchiella et al. 2015a |
| [11] | metal.com (2021) |

## Table A 2: **Costs of recycling facilities (lithium-ion batteries)**

| **LIB of Electric Vehicle** | | **Capacity**<br>*t.a* | **Investment**<br>*€* | **Fixed operating expenses**<br>*€/a* | **Economic Life span**<br>*a* | **Variable operation expenses***<br>*€/t* |
|---|---|---|---|---|---|---|
| **LIB recycling** | Building | | 3,648,000 | 66,000 | 40 | - |
| with black mass | Handling and discharge (incl. Transport) | 6,000 | 386,500 | 2,400 | 20 | 207 |
| as product | Disassembly | | 44,000 | 480 | 20 | 434 |
| | Mechanical processing (Solvent extraction) | | 6,171,000 | 684,000 | 20 | - |
| | **Total** | | **10,249,500** | **752,880** | **-** | **641** |
| **LIB Recycling** | Building | | 3,648,000 | 66,000 | 40 | - |
| with metal extraction | Handling and discharge (incl. Transport) | | 386,500 | 2,400 | 20 | 207 |
| from black mass | Disassembly | 6,000 | 44,000 | 480 | 20 | 434 |
| | Mechanical processing (Solvent extraction) | | 6,171,000 | 684,000 | 20 | - |
| | Hydro/Pyrometallurgical | | 9,750,500 | 1,080,755 | 20 | - |
| | **Total**** | | **20,000,000** | **1,767,635** | | **641** |

S: Thies et al.(2018)

* derived from Scenario results in Thies et al. (2018)

** Expert inverview; Construction costs of Hydro/Pyrometallurgical facility was a residual and hence is an estimation

## Table A 3: **Costs of recycling facilities (photovoltaic modules)**

| **PV Panel recycling**<br>Basic recycling | | **Capacity**<br>*t.a* | **Investment**<br>*€* | **Fixed operating expenses**<br>*€/a* | **Economic Life span**<br>*a* | **Variable operation expenses**<br>*€/t* |
|---|---|---|---|---|---|---|
| | Building* | | 1,824,000 | 33,000 | 40 | - |
| | Handling and Transport** | 2,000 | 128,833 | 800 | 20 | 205 |
| | Disassembly*** | | 14,667 | 480 | 20 | 163 |
| | **Total** | | **1,967,500** | **33,480** | | **368** |
| **PV Panel recycling** | Building* | | 1,824,000 | 33,000 | 40 | - |
| High efficiency recycilng | Handling and Transport** | 2,000 | 128,833 | 800 | 20 | 205 |
| | Disassembly*** | | 14,667 | 480 | 20 | 326 |
| | Processing facility**** | | 9,750,500 | 975,050 | 20 | - |
| | **Total** | | **11,718,000** | **1,009,330** | | **531** |

* Construction costs of building assumed to be 50% of the LIB-Recycling builiding in Thies et al. (2018)

** Handling and Transport assumed to be similar as in of the LIB-Recycling builiding in Thies et al. (2018); smaller analogous due to lower capacity

*** Disassembly assumed to be similar as in of the LIB-Recycling builiding in Thies et al. (2018); smaller analogous due to lower capacity

**** Process assumed to be as costly as Hydro/Pyrometallurgical Investment in Thies et al. (2018)

## Table A 4: **Costs for PV recycling facilities in this work compared to other literature**

| | | **Investigated Literature** | | | | **This work** | |
|---|---|---|---|---|---|---|---|
| | | Adamo et al. (2017) | Choi et al. (2014) | Choi et al. (2014) | Cucchiella et al. (2015b) | **Basic** | **High Eff** |
| Type | | c-Si | c-Si | Mixed | Mixed (80/20) | **c-Si** | **c-Si** |
| Capacity | t/a | 2,000 | 185 | 20,000 | 1,480 | **2,000** | **2,000** |
| Inv./Capital cost | €/t | 270 | 72 | 9 | 285 | **49** | **293** |
| Collection cost | €/t | 210 | 112 | 103 | 205 | **205** | **205** |
| Process costs | €/t | 320 | 1,052 | 53 | 326 | **163** | **326** |

Table A 5: **Recovery rates**

| E-Car | | | | |
|---|---|---|---|---|
| | **Werte** | Summe von MASS FLOWS in g/vehicle | Summe von SECONDARY RESOURCES - Base case | Summe von SECONDARY RESOURCES - High efficiency recycling |
| **chemicals** | **acrylic acid** | 948 | - | 0 |
| **chemicals Ergebnis** | | 948 | - | 0 |
| **Ferrous met** | **Cast iron** | 8 | 1 | 5,29859192 |
| | **ferrite** | 1.485 | - | 0 |
| | **iron** | 17.195 | 2.786 | 10832,9169 |
| | **molybdenum** | 0 | - | 0,00608156 |
| | **nickel** | 0 | - | 0,00019318 |
| | **nickel, 99.5%** | 1 | 0 | 0,28731369 |
| | **pig iron** | 1.339 | 184 | 716,453185 |
| | **reinforced steel** | 9 | 1 | 5,35710022 |
| | **steel** | 625.354 | 101.307 | 393972,951 |
| | **steel, chromium steel 18/8** | 11.890 | 1.926 | 7490,98885 |
| | **steel, low-alloyed** | 121.615 | 19.702 | 76617,3126 |
| **Ferrous metal Ergebnis** | | 778.896 | 125.908 | 489641,572 |
| **Glass** | **flat glass** | 0 | - | 0 |
| | **funnel glass** | 3 | - | 0 |
| | **glass** | 28.721 | 2.068 | 8042,0189 |
| | **glass tube** | 1 | - | 0 |
| **Glass Ergebnis** | | 28.725 | 2.068 | 8042,0189 |
| **glass fibre** | **glass fibre** | 3.200 | - | 0 |
| | **glass fibre reinforced plastic** | 2.451 | - | 0 |
| **glass fibre Ergebnis** | | 5.652 | - | 0 |
| **minerals** | **barite** | 71 | - | 0 |
| **minerals Ergebnis** | | 71 | - | 0 |
| **monomers** | **butyl acrylate** | 19 | - | 0 |
| | **epoxy** | 0 | - | 0 |
| | **epoxy resin** | 859 | - | 0 |
| | **penolic resin** | 6 | - | 0 |
| | **phenolic resin** | 137 | - | 0 |
| | **polyester resin** | 201 | - | 0 |
| | **rubber** | 113.752 | 14.338 | 55758,4386 |
| **monomers Ergebnis** | | 114.974 | 14.338 | 55758,4386 |
| **NiCoMn** | **NiCoMn hydroxide** | 109.984 | 13.858 | 61591,2016 |
| **NiCoMn Ergebnis** | | 109.984 | 13.858 | 61591,2016 |
| **Non-ferrous** | **aluminium** | 158.410 | 19.960 | 77620,8653 |
| | **aluminium wrought alloy** | 50.792 | 6.400 | 24888,2417 |
| | **brass** | 1.826 | 141 | 549,649191 |
| | **cable** | 2.389 | 185 | 719,183471 |
| | **copper** | 137.770 | 10.663 | 41468,827 |
| | **copper, primary** | 3.174 | 246 | 955,372455 |
| | **copper, secondary** | 563 | 44 | 169,521818 |
| | **lead** | 44.438 | 4.159 | 16175,6058 |
| | **magnesium** | 10.865 | - | 2966,15582 |
| | **molybdenum** | 1 | - | 0,27311643 |
| | **nickel, 99.5%** | 46 | - | 18,6690332 |
| | **Pb37** | 0 | 0 | 0,00195374 |
| | **tin** | 191 | 26 | 100,330096 |
| | **zinc** | 402 | 25 | 98,4343597 |
| **Non-ferrous metal Ergebnis** | | 410.869 | 41.849 | 165.731 |
| **other** | **aluminium oxide** | 84 | 11 | 41 |
| | **boric oxide** | 48 | 0 | 0 |
| | **bromine** | 0 | - | - |
| | **carboxymethyl cellulose, powder** | 948 | - | - |
| | **chromium** | 0 | 0 | 0 |
| | **coke** | 14 | - | - |
| | **Dry lamination** | 16 | - | - |
| | **electric connector** | 0 | - | - |
| | **electronic component, passive** | 2.207 | - | - |
| | **ethylene carbonate** | 40.049 | - | - |
| | **glass-filled epoxy** | 0 | - | - |
| | **nickel pigmented aluminium oxid** | 5 | - | 2 |
| | **other** | 30.422 | - | - |
| | **paint** | 5.007 | - | - |
| | **palladium** | 0 | - | 0 |
| | **petroleum coke** | 588 | - | - |
| | **phenolic resin** | 15 | - | - |
| | **phosphorus, white, liquid** | 26 | - | - |
| | **polyphenylene sulfide** | 170 | - | - |
| | **resist** | 0 | - | - |
| | **silica sand** | 28 | - | - |
| | **silicon** | 119 | - | - |
| | **silicon, electronics grade** | 0 | - | - |
| | **silicon, metallurgical grade** | 0 | - | - |
| | **silicone product** | 12 | - | - |
| | **SiO2** | 0 | - | - |
| | **(Leer)** | 1.707 | - | - |
| **other Ergebnis** | | 81.466 | 11 | 44 |
| **polymers** | **ABS** | 2.720 | 196 | 762 |
| | **acrylonitrile-butadiene-styrene c** | 562 | 40 | 157 |
| | **nylon 6** | 852 | - | - |
| | **nylon 66** | 25.994 | - | - |
| | **Oriented nylon** | 62 | - | - |
| | **PC** | 30 | - | - |
| | **PET** | 421 | - | - |
| | **pitch** | 6 | - | - |
| | **plastic** | 29.288 | 3.690 | 14.351 |
| | **polycarbonate** | 2 | - | - |
| | **polyester resin** | 639 | - | - |
| | **polyethylene** | 32.893 | - | - |
| | **polyethylene terephthalate, gran** | 59 | - | - |
| | **polyethylene, linear low density,** | 16 | - | - |
| | **polyethylene, low density, granul** | 44 | - | - |
| | **polymer, pitch** | 149 | - | - |
| | **polyphenylene sulfide** | 438 | - | - |
| | **polypropylene** | 564 | 41 | 161 |
| | **polypropylene, granulate** | 125 | - | 36 |
| | **polystyrene** | 609 | 7 | 174 |
| | **PP** | 15.988 | 1.176 | 4.573 |
| | **PVC** | 14 | - | - |
| | **synthetic rubber** | 24 | - | - |
| **polymers Ergebnis** | | 111.499 | 5.151 | 20.214 |
| **precious me** | **gold** | 6 | 0 | 1 |
| | **palladium** | 0 | - | 0 |
| | **silver** | 80 | 4 | 17 |
| **precious metal Ergebnis** | | 86 | 4 | 17 |
| **specialty me** | **antimon** | 0 | - | 0 |
| | **neodymium oxide** | 523 | - | 4 |
| | **lithium hexafluorphophate** | 5.461 | - | 3.823 |
| **specialty metal Ergebnis** | | 5.984 | - | 3.827 |
| **synthetic gra** | **synthetic graphite** | 45.511 | - | 31.858 |
| **synthetic grapite Ergebnis** | | 45.511 | - | 31.858 |
| **(Leer)** | **steel, low-alloyed** | 7.851 | 1.272 | 4.946 |
| **(Leer) Ergebnis** | | 7.851 | 1.272 | 4.946 |
| **Gesamtergebnis** | | 1.702.515 | 204.458 | 841.670 |

Table continued on the next page

| Wind Power Plant | | | | |
|---|---|---|---|---|
| | Werte | Summe von MASS FLOWS AT 2018 in kg/MW | Summe von SECONDARY RESOURCES - Base case | Summe von SECONDARY RESOURCES - High efficiency recycling |
| concrete | concrete | 404.570 | 37220,44 | 260.543 |
| concrete Ergebnis | | 404.570 | 37220,44 | 260.543 |
| elastomere | synthetic rubber | 0 | - | - |
| | tube insulation, elastomere | 1 | - | - |
| elastomere Ergebnis | | 1 | 0 | - |
| ferrous meta | cast iron | 20.330 | 1.870 | 13.093 |
| | chromium | 0 | - | - |
| | high alloyed steel | 13.000 | 1.196 | 8.372 |
| | low alloyed steel | 103.920 | 9.561 | 66.924 |
| | manganese | 0 | - | - |
| | molybdenum | 0 | - | - |
| | nickel, 99.5% | 0 | - | - |
| | nickel, class 1 | 0 | - | - |
| | pig iron | 1 | 0 | 1 |
| | sheet, low-alloyed steel, hot roll | 345 | 32 | 222 |
| | steel, low-alloyed | 0 | 0 | 0 |
| ferrous metal Ergebnis | | 137.596 | 12658,8425 | 88.612 |
| monomers | epoxy resin | 4 | - | - |
| | phenolic resin | 0 | - | - |
| monomers Ergebnis | | 4 | 0 | - |
| non-ferrous | aluminium oxide | 0 | - | - |
| | aluminium wrought alloy | 0 | 0 | 0 |
| | Aluminium, and alloys | 2.960 | 272 | 1.906 |
| | aluminium, wrought alloy | 10 | 1 | 7 |
| | brass | 0 | - | - |
| | copper | 1.463 | 139 | 973 |
| | copper alloys | 20 | 2 | 13 |
| | copper, cathode | 23 | 2 | 15 |
| | lead | 1 | - | - |
| | magnesium oxide | 0 | - | - |
| | tin | 1 | - | 0 |
| | zinc | 0 | - | 0 |
| | zinc coat, pieces | 47 | - | 20 |
| non-ferrous metal Ergebnis | | 4.527 | 416,403995 | 2.936 |
| other | barite | 0 | - | - |
| | ceramic/glass | 20 | - | - |
| | chemcial, inorganic | 1 | - | - |
| | coolant/other glycols | 160 | - | - |
| | ethylene glycol | 1 | - | - |
| | ferrite | 3 | - | - |
| | flat glass | 0 | - | - |
| | funnel glass | 5 | - | - |
| | glass fibre | 0 | - | - |
| | glass fibre reinforced plastic | 9 | - | - |
| | glass tube | 0 | - | - |
| | kraft paper | 0 | - | - |
| | lacquers | 210 | - | - |
| | lime, packed | 0 | - | - |
| | lubricants | 510 | - | - |
| | methyl acrylate | 0 | - | - |
| | modified organic natural materials | 60 | - | - |
| | not specified | 50 | - | - |
| | phosphorus, white, liquid | 0 | - | - |
| | SF6 Gas | 3 | - | - |
| | silica sand | 0 | - | - |
| | silicon, electronics grade | 0 | - | - |
| | silicon, metallurgical grade | 0 | - | - |
| | tetrafluoroethylene | 0 | - | - |
| | titanium dioxide | 0 | - | - |
| other Ergebnis | | 1.032 | 0 | - |
| polymers | nylon 6 | 1 | - | - |
| | polycarbonate | 11 | - | - |
| | polyethelyne, high density, granulate | 16 | - | - |
| | polyethelyne, low density, granulate | 1 | - | - |
| | polyethylene | 0 | - | - |
| | polyethylene terephtalate, granulate | 0 | - | - |
| | polyethylene terephthalate, granulate | 0 | - | - |
| | polyethylene, high density, granulate | 242 | - | - |
| | polymers | 8.610 | - | - |
| | polyphenylene sulfide | 1 | - | - |
| | polypropylene, granulate | 0 | - | - |
| | polyurethane, flexible foam | 0 | - | - |
| | polyvinylchloride, emulsion polymeri | 3 | - | - |
| | polyvinylchloride, suspension polyme | 18 | - | - |
| | silicone product | 0 | - | - |
| polymers Ergebnis | | 8.903 | 0 | - |
| precious me | gold | 0 | - | 0 |
| | palladium | 0 | - | 0 |
| | silver | 0 | - | 0 |
| precious metal Ergebnis | | 0 | 0 | 0 |
| specialty me | Magnets | 50 | - | - |
| | tantalum, powder, capacitor-grade | 0 | - | - |
| | zircon, 50% zirconium | 0 | - | - |
| specialty metal Ergebnis | | 50 | 0 | - |
| CFK/GFK | ceramic/glass | 7.520 | - | 2.632 |
| CFK/GFK Ergebnis | | 7.520 | 0 | 2.632 |
| Gesamtergebnis | | 564.204 | 50.296 | 354.723 |

Table continued on the next page

**PV**

| | Werte | Summe von MASS FLOWS AT in g/Wp | Summe von SECONDARY RESOURCES - Base case | Summe von SECONDARY RESOURCES - High efficiency recycling |
|---|---|---|---|---|
| chemical | acrylic acid | 0,01165414 | 0 | 0 |
| | aluminium oxide | 0,00104501 | 0 | 0 |
| | bromium | 0,0003905 | 0 | 0 |
| | butyl acrylate | 0,00023308 | 0 | 0 |
| | carboxymethyl cellulose, p | 0,01165414 | 0 | 0 |
| | ethylene carbonate | 0,49227068 | 0 | 0 |
| | ethylene glycol | 0,11370029 | 0 | 0 |
| | magnesium oxide | 4,002E-05 | 0 | 0 |
| | methyl acrylate | 9,5212E-07 | 0 | 0 |
| | NiCoMn hydroxide | 1,3518797 | 0 | 0 |
| | organic chemicals | 0,08405594 | 0 | 0 |
| | phosphor | 0,00579237 | 0 | 0 |
| | Sb2O3 | 0,00041962 | 0 | 0 |
| | SiO2 | 0,01430326 | 0 | 0 |
| | tetrafluorethylene | 0,0001905 | 0 | 0 |
| | titanium dioxide | 5,7127E-06 | 0 | 0 |
| | zircon | 0,00734661 | 0 | 0 |
| chemical Ergebnis | | 2,09498252 | 0 | 0 |
| Ferrous metal | chromium steel | 0,07527619 | 0,06774857 | 0,06774857 |
| | ferrite | 3,98606457 | 0 | 0 |
| | iron | 0,09550017 | 0,08595015 | 0,08595015 |
| | manganese | 0,00136698 | 0 | 0 |
| | molybdänum | 0,00160054 | 0 | 0 |
| | nickel | 0,00811648 | 0 | 0 |
| | reinforced steel | 2,19733333 | 1,9776 | 1,9776 |
| | steel | 16,2692971 | 14,6423674 | 14,6423674 |
| | steel, low-alloyed | 0,80845499 | 0,72760949 | 0,72760949 |
| Ferrous metal Ergebnis | | 23,4430104 | 17,5012756 | 17,5012756 |
| glass | glass | 0,17340664 | 0 | 0 |
| | solar glass, low-iron | 63,6610295 | 5,72949266 | 56,021706 |
| glass Ergebnis | | 63,8344362 | 5,72949266 | 56,021706 |
| monomers | epoxy resin | 3,19688155 | 0 | 0 |
| | glass-filled epoxy | 0,01284569 | 0 | 0 |
| monomers Ergebnis | | 3,20972725 | 0 | 0 |
| Non-ferrous metal | aluminium | 39,7930516 | 36,6096074 | 37,4054685 |
| | brass | 0,00059786 | 0 | 0 |
| | copper | 3,93662602 | 2,83437073 | 3,54296342 |
| | copper, primary | 0,03901338 | 0,02808964 | 0,03511205 |
| | copper, secondary | 0,00692256 | 0,00498424 | 0,0062303 |
| | lead | 0,03012068 | 0 | 0,02048206 |
| | Pb37 | 0,00168007 | 0 | 0 |
| | tin | 0,13644606 | 0,10233455 | 0,10233455 |
| | zinc | 0,04648066 | 0,02881801 | 0,02881801 |
| Non-ferrous metal Ergebnis | | 43,9909388 | 39,6082046 | 41,1414088 |

**PV**

| | Werte | Summe von MASS FLOWS AT in g/Wp | Summe von SECONDARY RESOURCES - Base case | Summe von SECONDARY RESOURCES - High efficiency recycling |
|---|---|---|---|---|
| other | brazing solder, cadmium free | 0 | 0 | 0 |
| | concrete | 0,00016366 | 8,1829E-05 | 0,00014729 |
| | diode, unspecified | 0,02030505 | 0 | 0 |
| | Dry lamination | 0,00019113 | 0 | 0 |
| | electronic component, passive | 0,02713083 | 0 | 0 |
| | glass fibre | 0,00048947 | 0 | 0 |
| | polyphenylene sulfide | 0,00208842 | 0 | 0 |
| | quartz | 0,01206368 | 0 | 0 |
| | resist | 0,00167553 | 0 | 0 |
| | synthetic graphite | 0,5593985 | 0 | 0 |
| | (Leer) | 0,08810526 | 0 | 0 |
| other Ergebnis | | 0,71161152 | 8,1829E-05 | 0,00014729 |
| polymers | acrylonitrile-butadiene-styrene | 0,04033564 | 0 | 0 |
| | EVA | 6,32274697 | 0 | 0 |
| | glass fibre reinforced plastic, pc | 3,25080583 | 0 | 0 |
| | nylon 6 | 0,00777962 | 0 | 0 |
| | nylon 66 | 0,31950977 | 0 | 0 |
| | Oriented nylon | 0,00076451 | 0 | 0 |
| | phenolic resin | 0,01097976 | 0 | 0 |
| | Polycarbonate, PC | 1,50807299 | 0 | 0 |
| | Polyethylene | 2,53669972 | 0,00042794 | 0,00042794 |
| | polyethylene, HDPE, granulate | 0,18249575 | 0 | 0 |
| | polypropylene, PP | 0,23114309 | 0 | 0 |
| | polyvinylfluoride film | 0,80931161 | 0 | 0 |
| | PPS | 0,09716228 | 0 | 0 |
| | PUR | 1,1456E-05 | 0 | 0 |
| | PVC | 0,02810517 | 0 | 0 |
| | SAN (Styrene acrylonitrile) | 0,00540541 | 0 | 0 |
| | Silicone product | 0,88158683 | 0 | 0 |
| | synthetic rubber | 0,01031114 | 0 | 0 |
| | thermoplastic elastomer | 0,45714286 | 0 | 0 |
| polymers Ergebnis | | 16,7003704 | 0,00042794 | 0,00042794 |
| Precious me | gold | 0,00049131 | 7,3696E-05 | 0,00044218 |
| | silver | 0,08883623 | 0 | 0,08350605 |
| Precious metal Ergebnis | | 0,08932753 | 7,3696E-05 | 0,08394823 |
| silicon | silicon | 7,69247182 | 0 | 7,30506948 |
| silicon Ergebnis | | 7,69247182 | 0 | 7,30506948 |
| Specialty me | antimon | 0,00040866 | 0 | 0 |
| | bismuth | 0,00277564 | 0 | 0 |
| | tantalum | 0,01397876 | 0 | 0 |
| Specialty metal Ergebnis | | 0,01716307 | 0 | 0 |
| Gesamtergebnis | | 161,78404 | 62,8395564 | 122,053983 |

## Table A 6: **Macroeconomic effects, total**

| | **GDP** | | | | **Employment** | | | | **Gate Fee** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **LIB** | | **PV module** | | **LIB** | | **PV module** | | **LIB** | | **PV module** | |
| | Base | High | Base | High | Base | High | Base | High | Base | High | Base | High |
| | *Mio.€* | | | | *Full Time Equivalents* | | | | *Mio.€* | | | |
| **2020** | - | - | - | - | - | - | - | - | 0 | 0 | 0 | 0 |
| **2021** | - | - | - | - | - | - | - | - | 0 | 0 | 0 | 0 |
| **2022** | - | - | - | - | - | - | - | - | 0 | 0 | 0 | 0 |
| **2023** | - | - | - | - | 1 | - | - | - | 0 | 0 | 0 | 0 |
| **2024** | - | - | - | - | 1 | - | - | - | 0 | 0 | 0 | 0 |
| **2025** | -0 | - | - | - | 1 | - | - | - | 0 | 0 | 0 | 0 |
| **2026** | 4 | 10 | - | - | 57 | 116 | - | - | -2 | -3 | 0 | 0 |
| **2027** | -2 | - | - | - | -4 | 6 | - | - | -3 | -2 | 0 | 0 |
| **2028** | -4 | 3 | - | - | -1 | 29 | 0 | - | -4 | -2 | 0 | 0 |
| **2029** | -6 | 7 | - | - | 3 | 68 | 0 | 0 | -7 | -1 | 0 | 0 |
| **2030** | -5 | 23 | - | - | 65 | 233 | 0 | 0 | -12 | -2 | 0 | 0 |
| **2031** | -16 | 22 | - | - | 14 | 196 | 0 | 1 | -17 | 0 | 0 | 0 |
| **2032** | -18 | 44 | - | 0 | 82 | 413 | 1 | 1 | -26 | 0 | 0 | 0 |
| **2033** | -22 | 67 | 0 | 1 | 146 | 643 | 2 | 4 | -37 | -2 | 0 | 0 |
| **2034** | -39 | 72 | 1 | 7 | 96 | 669 | 17 | 75 | -49 | -1 | 0 | -1 |
| **2035** | -47 | 100 | 2 | 8 | 166 | 943 | 23 | 84 | -63 | -2 | 0 | -2 |
| **2036** | -66 | 109 | 4 | 17 | 121 | 1,003 | 46 | 171 | -77 | 0 | -1 | -3 |
| **2037** | -75 | 141 | 6 | 22 | 194 | 1,309 | 68 | 211 | -94 | 0 | -1 | -4 |
| **2038** | -90 | 162 | 11 | 48 | 207 | 1,499 | 136 | 470 | -110 | 0 | -2 | -8 |
| **2039** | -106 | 183 | 15 | 59 | 219 | 1,690 | 182 | 552 | -127 | 0 | -3 | -10 |
| **2040** | -121 | 203 | 23 | 91 | 230 | 1,875 | 274 | 851 | -144 | 0 | -5 | -15 |
| **2041** | -135 | 222 | 28 | 104 | 240 | 2,047 | 338 | 955 | -159 | 0 | -7 | -20 |
| **2042** | -153 | 228 | 32 | 118 | 192 | 2,079 | 401 | 1,058 | -172 | 0 | -8 | -24 |
| **2043** | -158 | 253 | 37 | 129 | 257 | 2,330 | 457 | 1,144 | -184 | 0 | -10 | -30 |
| **2044** | -172 | 253 | 38 | 124 | 202 | 2,310 | 479 | 1,073 | -193 | 0 | -11 | -33 |
| **2045** | -183 | 250 | 38 | 118 | 149 | 2,256 | 488 | 986 | -198 | 0 | -12 | -35 |
| **2046** | -181 | 265 | 38 | 115 | 209 | 2,414 | 497 | 946 | -202 | 0 | -13 | -38 |
| **2047** | -181 | 265 | 37 | 105 | 210 | 2,418 | 486 | 829 | -202 | 0 | -13 | -38 |
| **2048** | -185 | 250 | 38 | 106 | 144 | 2,271 | 493 | 839 | -200 | 0 | -13 | -38 |
| **2049** | -181 | 246 | 38 | 107 | 146 | 2,230 | 496 | 840 | -196 | 0 | -13 | -39 |
| **2050** | -178 | 241 | 37 | 101 | 139 | 2,182 | 487 | 777 | -192 | 0 | -14 | -39 |

Table A 7: **Macroeconomic Effects – LIB**

| | **GDP Impact in Mio.€**<br>**LIB Recycling**<br>Base | | | | **GDP Impact in Mio.€**<br>**LIB Recycling**<br>High Efficiency | | | |
|---|---|---|---|---|---|---|---|---|
| | Direct & Indirect | Investment | Induced | Gate fee | Direct & Indirect | Investment | Induced | Gate fee |
| **2020** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2021** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2022** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2023** | -0 | 0 | 0 | -0 | 0 | 0 | -0 | 0 |
| **2024** | -0 | 0 | 0 | -0 | 0 | 0 | -0 | 0 |
| **2025** | -0 | 0 | 0 | -0 | 0 | 0 | -0 | 0 |
| **2026** | -0 | 5 | 1 | -1 | 0 | 10 | 2 | -2 |
| **2027** | -1 | 0 | 0 | -2 | 1 | 0 | 0 | -2 |
| **2028** | -1 | 0 | 0 | -3 | 4 | 0 | 0 | -1 |
| **2029** | -2 | 0 | 1 | -5 | 7 | 0 | 1 | -1 |
| **2030** | -3 | 5 | 2 | -9 | 12 | 10 | 3 | -2 |
| **2031** | -4 | 0 | 2 | -13 | 20 | 0 | 2 | -0 |
| **2032** | -6 | 5 | 3 | -20 | 30 | 10 | 4 | -0 |
| **2033** | -9 | 10 | 5 | -29 | 42 | 20 | 6 | -1 |
| **2034** | -12 | 5 | 5 | -38 | 56 | 10 | 6 | -0 |
| **2035** | -15 | 10 | 7 | -49 | 72 | 20 | 9 | -1 |
| **2036** | -19 | 5 | 8 | -60 | 90 | 10 | 9 | -0 |
| **2037** | -23 | 10 | 10 | -72 | 109 | 20 | 12 | -0 |
| **2038** | -27 | 10 | 11 | -85 | 128 | 20 | 13 | -0 |
| **2039** | -31 | 10 | 13 | -98 | 148 | 20 | 15 | -0 |
| **2040** | -35 | 10 | 14 | -111 | 167 | 20 | 16 | 0 |
| **2041** | -39 | 10 | 16 | -123 | 184 | 20 | 18 | -0 |
| **2042** | -42 | 5 | 16 | -132 | 200 | 10 | 17 | -0 |
| **2043** | -45 | 10 | 18 | -142 | 213 | 20 | 20 | -0 |
| **2044** | -47 | 5 | 18 | -149 | 224 | 10 | 19 | -0 |
| **2045** | -48 | 0 | 18 | -153 | 231 | 0 | 18 | -0 |
| **2046** | -49 | 5 | 19 | -156 | 234 | 10 | 20 | -0 |
| **2047** | -49 | 5 | 19 | -156 | 235 | 10 | 20 | 0 |
| **2048** | -49 | 0 | 18 | -154 | 232 | 0 | 19 | -0 |
| **2049** | -48 | 0 | 18 | -151 | 228 | 0 | 18 | -0 |
| **2050** | -47 | 0 | 17 | -148 | 223 | 0 | 18 | -0 |

Table A 8: **Macroeconomic effects – PV modules**

| | **GDP Impact in Mio.€**<br>**PV module**<br>Base | | | | **GDP Impact in Mio.€**<br>**PV module**<br>High Efficiency | | | |
|---|---|---|---|---|---|---|---|---|
| | Direct & Indirect | Investment | Induced | Gate fee | Direct & Indirect | Investment | Induced | Gate fee |
| **2020** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **2021** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2022** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2023** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2024** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2025** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2026** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2027** | 0 | 0 | -0 | 0 | 0 | 0 | -0 | 0 |
| **2028** | 0 | 0 | 0 | -0 | 0 | 0 | 0 | 0 |
| **2029** | 0 | 0 | 0 | -0 | 0 | 0 | 0 | 0 |
| **2030** | 0 | 0 | 0 | -0 | 0 | 0 | 0 | 0 |
| **2031** | 0 | 0 | 0 | -0 | 0 | 0 | 0 | 0 |
| **2032** | 0 | 0 | 0 | -0 | 0 | 0 | 0 | 0 |
| **2033** | 0 | 0 | 0 | -0 | 1 | 0 | 0 | 0 |
| **2034** | 0 | 1 | 0 | -0 | 1 | 6 | 1 | -1 |
| **2035** | 1 | 1 | 0 | -0 | 2 | 6 | 1 | -1 |
| **2036** | 2 | 2 | 0 | -1 | 5 | 12 | 2 | -3 |
| **2037** | 4 | 2 | 1 | -1 | 11 | 12 | 3 | -3 |
| **2038** | 7 | 5 | 1 | -2 | 18 | 30 | 6 | -6 |
| **2039** | 11 | 5 | 2 | -3 | 30 | 30 | 7 | -7 |
| **2040** | 16 | 8 | 3 | -4 | 43 | 47 | 11 | -12 |
| **2041** | 22 | 8 | 3 | -5 | 59 | 47 | 13 | -15 |
| **2042** | 27 | 8 | 4 | -7 | 74 | 47 | 15 | -19 |
| **2043** | 32 | 8 | 4 | -8 | 88 | 47 | 16 | -23 |
| **2044** | 36 | 6 | 4 | -9 | 99 | 36 | 16 | -26 |
| **2045** | 39 | 4 | 4 | -9 | 107 | 24 | 15 | -27 |
| **2046** | 41 | 3 | 4 | -10 | 112 | 18 | 15 | -29 |
| **2047** | 42 | 1 | 4 | -10 | 115 | 6 | 13 | -29 |
| **2048** | 43 | 1 | 4 | -10 | 117 | 6 | 14 | -29 |
| **2049** | 43 | 1 | 4 | -10 | 117 | 6 | 14 | -30 |
| **2050** | 43 | 0 | 4 | -10 | 118 | 0 | 13 | -30 |

Table A 9: **Assumption on O&M structure**

| CPA | CPA Code | Fixed Costs | Variable Costs |
|---|---|---|---|
| Computer, electronic and optical products | 26 | 25% | |
| Electrical equipment | 27 | | 25% |
| Machinery and equipment n.e.c. | 28 | | 25% |
| Repair a.installation services of machinery a.equipment | 33 | 25% | |
| Electrictiy and Supply Services | 35.1 | | 5% |
| Land transport services a. transport services via pipelines | 49 | | 30% |
| Information technology serv., communication services | 62-63 | | 5% |
| Financial services | 64 | | 5% |
| Insurance, reinsurance and pension funding services | 65 | | 5% |
| VALUE ADDED CATEGORY | | | |
| Wages and salaries | | 50% | |

## a. NPV calculation details

| | | | | **y1** | **y2** | **y3** | **y4** | **y5** | **y6** | **y7** | **y8** | **y9** | **y10** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EV base** | **EoL flow** | LIB cell | tons | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 |
| **Cap. 6000 t/a** | | LIB BMS, cooling | tons | 769 | 769 | 769 | 769 | 769 | 769 | 769 | 769 | 769 | 769 |
| | | Vehicle | tons | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 |
| | **Costs Facility** | Capital costs | Mio.€ | - 0.51 | - 0.49 | - 0.46 | - 0.44 | - 0.42 | - 0.40 | - 0.38 | - 0.36 | - 0.35 | - 0.33 |
| | | Fix Costs | Mio.€ | - 0.75 | - 0.72 | - 0.68 | - 0.65 | - 0.62 | - 0.59 | - 0.56 | - 0.54 | - 0.51 | - 0.49 |
| | | Variable Costs | Mio.€ | - 3.85 | - 3.66 | - 3.49 | - 3.32 | - 3.16 | - 3.01 | - 2.87 | - 2.73 | - 2.60 | - 2.48 |
| | **Costs Other** | Treatment BMS | Mio.€ | - 0.17 | - 0.16 | - 0.16 | - 0.15 | - 0.14 | - 0.14 | - 0.13 | - 0.12 | - 0.12 | - 0.11 |
| | | Treatment vehicle | Mio.€ | - 2.85 | - 2.71 | - 2.58 | - 2.46 | - 2.34 | - 2.23 | - 2.13 | - 2.02 | - 1.93 | - 1.84 |
| | **Revenues** | **Revenues** | Mio.€ | **- 0.69** | **- 0.66** | **- 0.63** | **- 0.60** | **- 0.57** | **- 0.54** | **- 0.51** | **- 0.49** | **- 0.47** | **- 0.44** |
| | | Taxes on Revenues | Mio.€ | 0.17 | 0.16 | 0.16 | 0.15 | 0.14 | 0.14 | 0.13 | 0.12 | 0.12 | 0.11 |
| | | **NPV** | Mio.€ | **- 8.65** | **- 8.24** | **- 7.84** | **- 7.47** | **- 7.12** | **- 6.78** | **- 6.45** | **- 6.15** | **- 5.85** | **- 5.57** |
| | | | €/t | ##### | ##### | ##### | ##### | ##### | ##### | ##### | ##### | - 975.61 | - 929.15 |
| | | | €/kg | - 1.44 | - 1.37 | - 1.31 | - 1.25 | - 1.19 | - 1.13 | - 1.08 | - 1.02 | - 0.98 | - 0.93 |

| | | | | **y1** | **y2** | **y3** | **y4** | **y5** | **y6** | **y7** | **y8** | **y9** | **y10** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EV base** | **EoL flow** | LIB cell | tons | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 | 6,000 |
| **Cap. 6000 t/a** | | LIB BMS, cooling | tons | 769 | 769 | 769 | 769 | 769 | 769 | 769 | 769 | 769 | 769 |
| | | Vehicle | tons | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 | 28,479 |
| | **Costs Facility** | Capital costs | Mio.€ | - 1.00 | - 0.95 | - 0.91 | - 0.86 | - 0.82 | - 0.78 | - 0.75 | - 0.71 | - 0.68 | - 0.64 |
| | | Fix Costs | Mio.€ | - 1.77 | - 1.68 | - 1.60 | - 1.53 | - 1.45 | - 1.38 | - 1.32 | - 1.26 | - 1.20 | - 1.14 |
| | | Variable Costs | Mio.€ | - 3.85 | - 3.66 | - 3.49 | - 3.32 | - 3.16 | - 3.01 | - 2.87 | - 2.73 | - 2.60 | - 2.48 |
| | **Costs Other** | Treatment BMS | Mio.€ | - 0.17 | - 0.16 | - 0.16 | - 0.15 | - 0.14 | - 0.14 | - 0.13 | - 0.12 | - 0.12 | - 0.11 |
| | | Treatment vehicle | Mio.€ | - 2.85 | - 2.71 | - 2.58 | - 2.46 | - 2.34 | - 2.23 | - 2.13 | - 2.02 | - 1.93 | - 1.84 |
| | **Revenues** | **Revenues** | Mio.€ | **13.01** | **12.39** | **11.80** | **11.24** | **10.70** | **10.19** | **9.71** | **9.24** | **8.80** | **8.38** |
| | | Taxes on Revenues | Mio.€ | - 3.25 | - 3.10 | - 2.95 | - 2.81 | - 2.68 | - 2.55 | - 2.43 | - 2.31 | - 2.20 | - 2.10 |
| | | **NPV** | Mio.€ | **0.12** | **0.12** | **0.11** | **0.10** | **0.10** | **0.10** | **0.09** | **0.09** | **0.08** | **0.08** |
| | | | €/t | 20.21 | 19.25 | 18.33 | 17.46 | 16.63 | 15.84 | 15.08 | 14.37 | 13.68 | 13.03 |
| | | | €/kg | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 |

| | | | | **y1** | **y2** | **y3** | **y4** | **y5** | **y6** | **y7** | **y8** | **y9** | **y10** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PV base** | **EoL flow** | PV Modules | tons | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 |
| **Cap. 2000 t/a** | | PV Mounting | tons | 698 | 698 | 698 | 698 | 698 | 698 | 698 | 698 | 698 | 698 |
| | | PV BOS | tons | 508 | 508 | 508 | 508 | 508 | 508 | 508 | 508 | 508 | 508 |
| | **Costs Facility** | Capital costs | Mio.€ | - 0.10 | - 0.09 | - 0.09 | - 0.08 | - 0.08 | - 0.08 | - 0.07 | - 0.07 | - 0.07 | - 0.06 |
| | | Fix Costs | Mio.€ | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.02 | - 0.02 | - 0.02 | - 0.02 |
| | | Variable Costs | Mio.€ | - 0.74 | - 0.70 | - 0.67 | - 0.64 | - 0.61 | - 0.58 | - 0.55 | - 0.52 | - 0.50 | - 0.47 |
| | **Costs Other** | Treatment Mounting | Mio.€ | - 0.04 | - 0.04 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.02 |
| | | Treatment BOS | Mio.€ | - 0.11 | - 0.11 | - 0.10 | - 0.10 | - 0.09 | - 0.09 | - 0.09 | - 0.08 | - 0.08 | - 0.07 |
| | **Revenues** | **Revenues** | Mio.€ | **1.08** | **1.03** | **0.98** | **0.93** | **0.89** | **0.85** | **0.81** | **0.77** | **0.73** | **0.70** |
| | | Taxes on Revenues | Mio.€ | - 0.27 | - 0.26 | - 0.24 | - 0.23 | - 0.22 | - 0.21 | - 0.20 | - 0.19 | - 0.18 | - 0.17 |
| | | **Revenues after Tax** | Mio.€ | **- 0.21** | **- 0.20** | **- 0.19** | **- 0.18** | **- 0.17** | **- 0.17** | **- 0.16** | **- 0.15** | **- 0.14** | **- 0.14** |
| | | | €/t | - 105.38 | - 100.36 | - 95.58 | - 91.03 | - 86.69 | - 82.57 | - 78.63 | - 74.89 | - 71.32 | - 67.93 |
| | | | €/kg | - 0.11 | - 0.10 | - 0.10 | - 0.09 | - 0.09 | - 0.08 | - 0.08 | - 0.07 | - 0.07 | - 0.07 |

| | | | | **y1** | **y2** | **y3** | **y4** | **y5** | **y6** | **y7** | **y8** | **y9** | **y10** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PV high** | **EoL flow** | PV Modules | tons | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 | 2,000 |
| **Cap. 2000 t/a** | | PV Mounting | tons | 698 | 698 | 698 | 698 | 698 | 698 | 698 | 698 | 698 | 698 |
| | | PV BOS | tons | 508 | 508 | 508 | 508 | 508 | 508 | 508 | 508 | 508 | 508 |
| | **Costs Facility** | Capital costs | Mio.€ | - 0.59 | - 0.56 | - 0.53 | - 0.51 | - 0.48 | - 0.46 | - 0.44 | - 0.42 | - 0.40 | - 0.38 |
| | | Fix Costs | Mio.€ | - 1.01 | - 0.96 | - 0.92 | - 0.87 | - 0.83 | - 0.79 | - 0.75 | - 0.72 | - 0.68 | - 0.65 |
| | | Variable Costs | Mio.€ | - 1.06 | - 1.01 | - 0.96 | - 0.92 | - 0.87 | - 0.83 | - 0.79 | - 0.75 | - 0.72 | - 0.68 |
| | **Costs Other** | Treatment Mounting | Mio.€ | - 0.04 | - 0.04 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.03 | - 0.02 |
| | | Treatment BOS | Mio.€ | - 0.11 | - 0.11 | - 0.10 | - 0.10 | - 0.09 | - 0.09 | - 0.09 | - 0.08 | - 0.08 | - 0.07 |
| | **Revenues** | **Revenues** | Mio.€ | **2.95** | **2.81** | **2.68** | **2.55** | **2.43** | **2.31** | **2.20** | **2.10** | **2.00** | **1.90** |
| | | Taxes on Revenues | Mio.€ | - 0.74 | - 0.70 | - 0.67 | - 0.64 | - 0.61 | - 0.58 | - 0.55 | - 0.52 | - 0.50 | - 0.48 |
| | | **NPV** | Mio.€ | **- 0.60** | **- 0.57** | **- 0.54** | **- 0.52** | **- 0.49** | **- 0.47** | **- 0.45** | **- 0.42** | **- 0.40** | **- 0.38** |
| | | | €/t | - 298.41 | - 284.20 | - 270.67 | - 257.78 | - 245.51 | - 233.81 | - 222.68 | - 212.08 | - 201.98 | - 192.36 |
| | | | €/kg | - 0.30 | - 0.28 | - 0.27 | - 0.26 | - 0.25 | - 0.23 | - 0.22 | - 0.21 | - 0.20 | - 0.19 |