Technology Collaboration Programme
by iea

International Energy Agency
Photovoltaic Power Systems Programme

Task 12 PV Sustainability

PVPS

# Resource Use Footprints of Residential PV Systems

2022

Report IEA-PVPS T12-22: 2022

# What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, and the United States of America. The European Commission, Solar Power Europe, the Smart Electric Power Alliance (SEPA), the Solar Energy Industries Association and the Cop- per Alliance are also members.

**Visit us at: www.iea-pvps.org**

# What is IEA PVPS Task 12?

Task 12 aims at fostering international collaboration in safety and sustainability that are crucial for assuring that PV grows to levels enabling it to make a major contribution to the needs of the member countries and the world. The overall objectives of Task 12 are to 1. Quantify the environmental profile of PV in comparison to other energy technologies; 2. Investigate end of life management options for PV systems as deployment increases and older systems are decommissioned; 3. Define and address environmental health & safety and other sustainability issues that are important for market growth. The first objective of this task is well served by life cycle assessments (LCAs) that describe the energy-, material-, and emission-flows in all the stages of the life of PV. The second objective is addressed through analysis of including recycling and other circular economy pathways. For the third objective, Task 12 develops methods to quantify risks and opportunities on topics of stakeholder interest. Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and the University of New South Wales (UNSW Sydney). Support from DOE and UNSW are gratefully acknowledged.

## Authors

➢ **Main Content:** Rolf Frischknecht, Luana Krebs

**DISCLAIMER**

The IEA PVPS TCP is organised under the auspices of the International Energy Agency (IEA) but is functionally and legally autonomous. Views, findings and publications of the IEA PVPS TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries

**COVER PICTURE**

"Sunrise Dam Mine, Western Australia", Source: Calistemon, CC BY-SA 4.0

**ISBN** 978-3-907281-25-3: Resource Use Footprints of Residential PV Systems

INTERNATIONAL ENERGY AGENCY
PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

# Mineral Resource Use Footprints of Residential PV Systems

## IEA PVPS
## Task 12: PV Sustainability

Report IEA-PVPS T12-22:2022

First published February 2022
Corrected version v1.2 posted April 2022*

ISBN 978-3-907281-25-3

**Task Managers**:
Garvin Heath, National Renewable Energy Laboratory, Golden, CO, USA
Jose Bilbao, University of New South Wales, Sydney, Australia

**Authors:**
Rolf Frischknecht, Luana Krebs

*Citation: R. Frischknecht, L. Krebs, 2022, Resource Use Footprints of Residential PV Systems, IEA PVPS Task 12, International Energy Agency (IEA) PVPS Task 12, Report T12-22:2022. ISBN 978-3-907281-25-3.*

*Minor correction to Table 3.1

# TABLE OF CONTENTS

# ACKNOWLEDGEMENTS

This report received valuable contributions from several IEA-PVPS Task 12 members as well as feedback from ExCo members which helped to further improve its contents.

# LIST OF ABBREVIATIONS

| | |
|---|---|
| a | year (annum) |
| AC | alternating current |
| ADP | Abiotic resource depletion potential |
| BAU | business as usual |
| CdTe | Cadmium Telluride |
| CED | cumulative energy demand |
| CED nr | non-renewable cumulative energy demand |
| CF | characterisation factor |
| CH | Switzerland |
| CIS | copper indium selenium |
| DC | direct current |
| DtT | distance to target |
| EF | environmental footprint |
| eq | equivalent |
| ER | economic reserves |
| GHG | greenhouse gas |
| GWP | global warming potential |
| GLO | global |
| IEA | International Energy Agency |
| KBOB | Coordination Group for Construction and Property Services (Koordinationskonferenz der Bau- und Liegenschaftsorgane des Bundes) |
| kWp | kilowatt peak |
| LCA | life cycle assessment |
| LCI | life cycle inventory analysis |
| LCIA | life cycle impact assessment |
| $LiFePO_4$ | iron phosphate lithium-ion |
| MJ | megajoule |
| MPP | maximum power point |
| MPPT | maximum power point tracker |
| mono-Si | monocrystalline silicon |
| multi-Si | multicrystalline silicon |
| NCM | nickel cobalt manganese oxide |

| | |
|---|---|
| NO | Norway |
| PM | particulate matter |
| PV | photovoltaic |
| PVPS | photovoltaic power systems |
| RER | Europe |
| Sb | Antimony (Latin: Stibium) |
| $SF_6$ | Sulfur hexafluoride |
| SOP | Surplus Ore Potential |
| tkm | tonne kilometre (unit for transportation services) |
| URR | Ultimate recoverable resources |
| UR | Ultimate reserves |
| UVEK | Federal Department of the Environment, Transport, Energy and Communications (Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation) |

# EXECUTIVE SUMMARY


Resource use intensity is often mentioned as one of the main characteristics of PV systems and PV electricity. Recently, the International Energy Agency published a report on the role of critical minerals in clean energy transitions. The Product Environmental Footprint pilot study on PV electricity quantified (among other environmental impacts) its abiotic depletion potential. So far, a comprehensive assessment of resource use impacts highlighting the different facets of its impacts is however lacking.

For the first time, the resource use impacts of PV electricity are quantified simultaneously with four impact category indicators recommended or suggested by the Life Cycle Initiative hosted at UN Environment. The indicators cover distinctly different aspects of resource use, namely resource depletion with the Abiotic Depletion Potential, ultimate reserves ($ADP_{UR}$), economic resource scarcity with the Abiotic Depletion Potential, economic reserves ($ADP_{ER}$), resource quality with the Surplus Ore Potential, Ultimate Recoverable Resources ($SOP_{URR}$) and resource criticality with the ESSENZ method.

The resource use impacts caused from the generation of 1 kWh electricity with a residential scale photovoltaic (PV) system installed in Central Europe using mono- and multi-crystalline silicon panels and CdTe panels, respectively are quantified. The product system includes manufacture, use and end of life treatment (take back and recycling) of the PV panels, cabling, inverter and supporting structure, the supply chains of the raw materials and energy used in PV panel and inverter manufacture as well as transport logistics.

The production of 1 kWh AC electricity produced with residential scale PV systems requires between 16 and 20 grams of primary mineral resources with up to 90% of them used in infrastructures such as factories and roads and in (solar) glass production and a few percent each being iron (supporting structure), aluminium (frame) and copper (cabling and inverter).

Resource use impacts on resource depletion and on resource quality are similar for all three PV technologies. Less than ten minerals and metals contribute to at least 95 % of the overall score of all four resource use impact indicators. Gold, silver and copper are always in the top ten minerals and metals (see Fig. 1.1). While Gold is mainly used in the inverter electronics and copper in the cabling and in the inverter, silver is mainly used in crystalline silicon panels and in the inverter electronics.

Tellurium (CdTe panel and inverter electronics), tin (inverter electronics) as well as gravel and sand (infrastructures and panel glass) are important substances regarding resource criticality (ESSENZ).

The inverter often contributes most to the resource use impacts followed by the PV panel. The alloying elements used in the supporting structure contribute significantly to the surplus ore potential (SOP).

The study contributes to better understand the various and multi-facetted resource use impacts of different PV systems. The study helps readers to choose the resource use indicator appropriate for their question or concern. The results help to identify which metals and/or minerals could be targets for reduction in use (increase material efficiency) and for increase in resource recovery during end-of-life treatment. Depending on the indicator (and on the resource use related question at stake) this may be different metals and/or minerals.

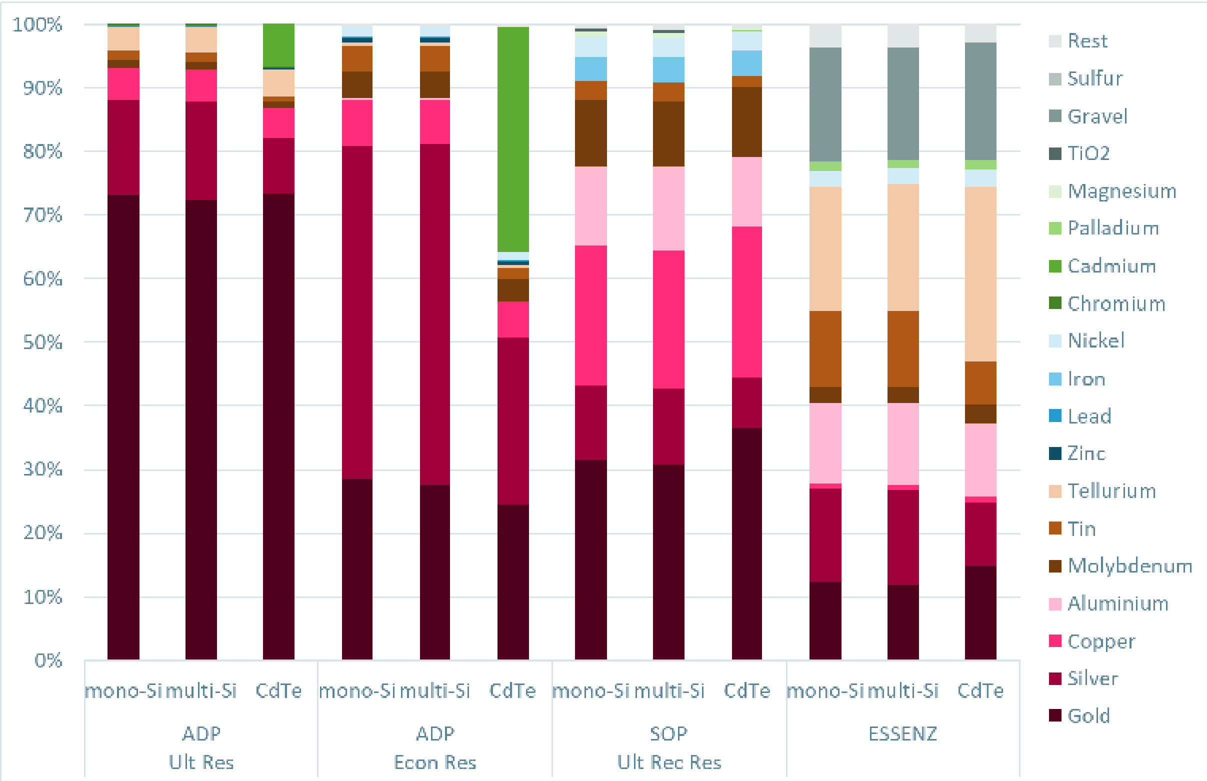


**Fig. 1.1 Relative contribution of different metals and minerals to the resource use impacts, quantified with the Abiotic Depletion Potential (ADP), ultimate reserves, the Abiotic Depletion Potential (ADP), economic reserves, the Surplus Ore Potential (SOP) and the resource criticality indicator ESSENZ, per kWh AC electricity produced with residential scale PV systems operated in central Europe; average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

Information and data on the share of minerals and metals recovered during collection, treatment and recycling of panels, inverters, cabling and supporting structures would allow to quantify the impacts on depletion, scarcity, quality, and criticality of consumptive resource use. This information and data should be collected for metals and minerals contributing significantly to resource use impacts including Gold, silver, copper, tellurium and tin, and the respective life cycle inventory datasets should be complemented accordingly.

Future research should establish recovery rates of the most important minerals and metals achieved and achievable in commercially operated recycling facilities of crystalline silicon, CIS and CdTe panels as well as inverters and electric installations. Such information should then be embedded in the life cycle inventories of PV systems and their supply chains.

# 1 INTRODUCTION AND OBJECTIVE

Resource use intensity is often mentioned as one of the main characteristics of PV systems and PV electricity. Recently, the International Energy Agency published a report on the role of critical minerals in clean energy transitions (IEA 2021) quantifying the total amount of copper, silicon and silver needed by solar PV in 2030 and 2040 depending on the scenario applied. The Product Environmental Footprint pilot study on PV electricity (TS PEF Pilot PV 2019) quantified (among other environmental impacts) its abiotic depletion potential per kWh electricity. So far, a comprehensive assessment of resource use impacts on a per unit basis, highlighting the different facets of those impacts and identifying the key driving metals and minerals is however lacking.

In the recent past, the Life Cycle Initiative hosted by UN Environment[1] has run a project on the harmonisation of environmental life cycle impact assessment indicators. The results of the first two phases are documented in two reports containing best available recommended characterisation factors for greenhouse gas emissions, human health impacts caused by fine particles emissions and formation, land use related impacts on biodiversity, water use related impacts on water scarcity and human health (Frischknecht & Jolliet 2016), and on eutrophication and acidification, human and eco-toxicity, land use related impacts on soil quality and resource use impacts (Frischknecht & Jolliet 2019).

IEA PVPS Task 12 decided to profit from this work and, for the first time to use several recommended and suggested resource use indicators and assess resource use impacts on electricity production with residential scale PV systems from different perspectives. The experts selected four resource use impact indicators which address distinctly different aspects of resource use.

This study contributes to better understand the resource use impacts of different PV systems and their most important contributors to resource use impacts, which, once identified, can become targets for R&D to reduce them. The results reported in this study can be compared to those of other technologies assessed with the same indicators and on a life cycle basis and using the same system boundary. The results complement assessments of life cycle based greenhouse gas emissions of PV systems and other technologies.

While results applying four distinctly different indicators are shown in this report, it is recommended to choose the most appropriate indicator based on the resource use related question the indicator is addressing.

The scope of the assessment is described in Chapter 2, with the definition of the functional unit (Subchapter 2.1), the description of the PV system design (Subchapter 2.2), the allocation principles applied (Subchapter 0), the data sources used (Subchapter 2.4) and a description of the four resource use indicators (Subchapter 2.5). Chapter 3 contains a coarse description of the life cycle inventory data used including a table with the key characteristics and parameter of the PV systems and their supply chains. Chapter 4 contains the description and discussion of the cumulative resource use impacts and considerations regarding data quality and uncertainty. Conclusions and recommendations are given in Chapter 5.

[1] www.lifecycleinitative.org, accessed on 24 February 2021

# 2 SCOPE

## 2.1 Functional Unit

The functional unit is defined as the generation of 1 kWh of AC electricity measured at the output of the inverter of residential scale PV systems.

## 2.2 System Design

The LCA includes all components of a 3 kWp PV system installed on a pitched roof of a residential building in central Europe (see also Fig. 2.1):

- Production and end of life treatment of the PV panels;
- Production and end of life treatment of the inverter;
- Production and end of life treatment of the mounting structure;
- Production and end of life treatment of electric cabling;
- Operation of the PV system;

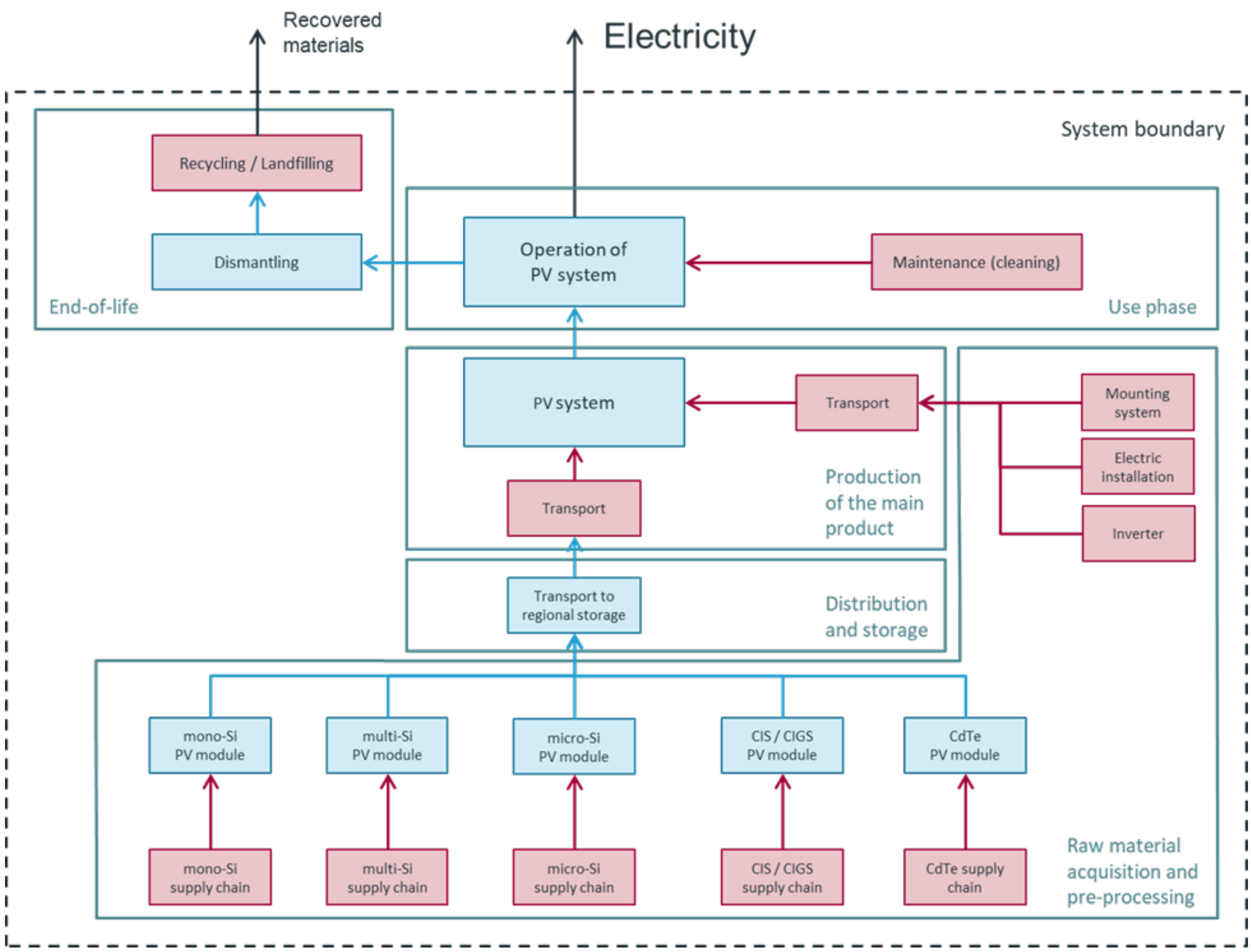


**Fig. 2.1 Product system of PV electricity production, adapted from TS PEF Pilot PV 2019**

The end of life treatment includes takeback and treatment of panels and inverters according to WEEE and as described in another IEA PVPS Task 12 report (Stolz et al. 2016).

The treatment of PV panels and electronic waste is part of the product systems analysed. However, the amounts of metals and minerals recovered during panel treatment and during the treatment and recycling of electric cabling, inverters, supporting structure are not systematically and consistently quantified in the life cycle inventories used in this assessment. That is why resources extraction rather than consumptive use of resources is assessed.

## 2.3 Allocation

The assessed PV systems includes end of life treatment, which is a multi-output process providing the waste treatment service and producing secondary materials for further use. Economic allocation is applied on this treatment process. Economic allocation is also applied on the recovery of tellurium from an anode slime from which copper and silver is recovered too.

## 2.4 Data Sources

For assessing production and installation of the PV system, datasets from the PVPS Task 12 LCI update 2020 (Frischknecht et al. 2020) are used. For other processes, such as background processes for which no specific data were collected, the datasets in the UVEK LCA data DQRv2:2021 are used (KBOB et al. 2022).

## 2.5 Mineral resource use indicators

### *2.5.1 Overview*

Natural resources include minerals and metals, air components, fossil fuels, renewable energy sources, water, land and water surface, soil, and biotic natural resources such as wild flora and fauna (Sonderegger et al. 2017). This report focuses on mineral resources excluding energy carriers (e.g., coal). Assessing the impacts of resource use is debated and even the area of protection “Natural Resources” remains controversial. Some argue that the availability and scarcity of mineral resources is reflected in their prices whereas others claim that the demand of future (unborn) generations is not reflected in these prices and is thus due for separate consideration.

For about one decade the Life Cycle Initiative hosted at UN Environment[2] has been running a project on the harmonisation of environmental life cycle impact assessment indicators. This effort resulted in a set of recommended impact assessment indicators covering climate change, human health impacts caused by fine particles, land use impacts on biodiversity, water scarcity, eutrophication and acidification, human toxicity, eco-toxicity, soil related eco-system services and impacts related to the use of mineral resources.

During this harmonisation process the Task Force on Mineral Resources agreed on the following definition of the area of protection (Frischknecht & Jolliet 2019, p. 105):

> *“Within the area of protection “Natural Resources”, the safeguard subject for “mineral resources” is the potential to make the value of mineral resources usable for humans in the technosphere. The damage is quantified as the reduction or loss of this potential caused by human activity. Mineral resources are chemical elements (e.g., copper), minerals (e.g., gypsum), and aggregates (e.g., sand) as embedded in a natural or anthropogenic stock.”*

The following text and figure are taken from the final report published by UN Environment (Frischknecht & Jolliet 2019). Several characterisation models have been developed to

[2] www.lifecycleinitiative.org, accessed 17.2.2021

connect life cycle inventory flows of mineral resources to a variety of impact indicators, which measure different aspects or impacts of natural resource use. As shown in the grey material flow layer in Fig. 2.2, natural stocks of mineral resources exist within the lithosphere, with significant spatial variability in the quantity and quality of these resources. Exploration processes identify these natural resources and classify them based upon geological and economic uncertainty. Through extraction and further industrial processing, these materials are transformed for use in the technosphere. They may remain within the in-use stock for a period before being reused, recycled, or transferred to landfills. Furthermore, materials might be dissipated at any point in the value chain.

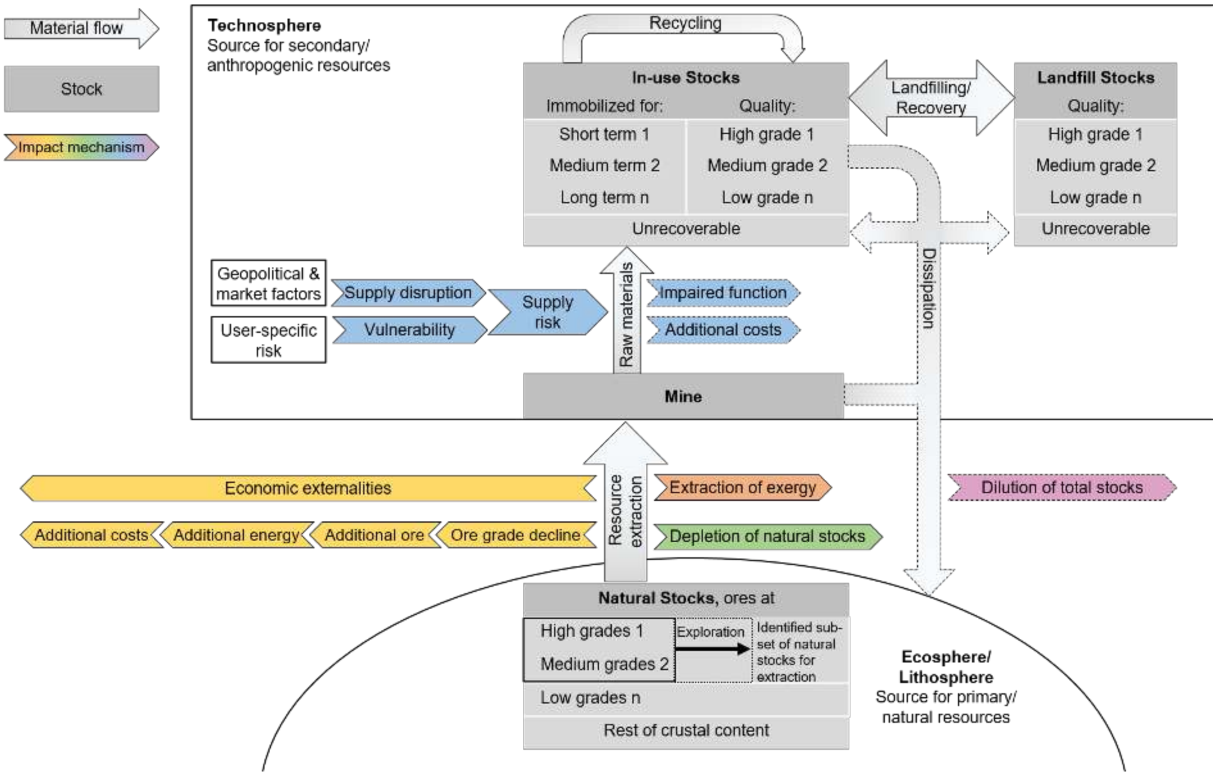


**Fig. 2.2 Material flow (grey layer) and impact mechanisms overview, presented in colour for depletion methods (green), future effort methods (yellow), thermodynamic accounting methods (orange), supply risk methods (blue), and the "dilution of total stocks" approach (purple). Dashed material flows and impact mechanisms are proposed or discussed but not agreed, operational, or published yet (Figure from Sonderegger et al. 2020, published in Frischknecht & Jolliet 2019).**

There are numerous indicators available to address and quantify the impacts of the extraction of mineral resources. The Task Force on Resource Use of the Life Cycle Initiative hosted at UN Environment[3] described and characterised the different indicators and grouped them into methods on

- Depletion (green arrow in Fig. 2.2);
- Future efforts (yellow arrows);
- Thermodynamic accounting (orange arrow); and
- Supply risks (blue arrows).

[3] www.lifecycleinitiative.org, accessed 17.2.2021

Other methods based on market prices, such as the Commodity-Life Cycle Costing (C-LCC) indicator developed by Mela et al. (Mela et al. 2021) were not in the scope of the harmonisation efforts of the Life Cycle Initiative.

Finally, the group agreed to recommend, interim recommend or suggest seven indicators. In this report, the following four resource use indicators are selected and applied on the LCA of PV electricity (level of UN Environment recommendation[4] in brackets, and indicating the reason for the choice):

1. Abiotic Resource Depletion Potential, ultimate reserves (recommended): this indicator is being used in the Environmental Footprint impact assessment method published by the European Commission. It has the highest recommendation level of methods addressing depletion.
2. Abiotic Resource Depletion Potential, economic reserves (suggested): this indicator has often been used in the past to assess resource use impacts and allows to see the difference between a short-term perspective (economic reserves) and a long-term perspective (ultimate reserves) of resource depletion.
3. Surplus Ore Potential (interim recommended): this indicator has the highest recommendation level of the “future effort” resource indicators.
4. ESSENZ (integrated method to assess resource efficiency; interim recommended): this indicator has the highest recommendation level of the “supply risk” resource indicators

Thermodynamic accounting indicators were not selected because of lack of appropriate life cycle inventory data and information. The four methods selected for this study sufficiently represent the broad spectrum of resource use indicators and their ability to answer specific resource use related questions (see Sections below).

The four methods are characterised in the following sections. The text is based on the descriptions in Chapter 5 of Frischknecht & Jolliet (ed.) (2019) and cites the leading question, to which each of the indicators provides an answer.

### *2.5.2 Abiotic Depletion Potential, ultimate reserves*

The Abiotic Depletion Potential, ultimate reserves ($ADP_{UR}$) indicator relates annual extraction rates to a stock estimate. Depletion of a mineral or metal is assessed (see Equation 1[5]) with the ratio of its annual extraction ($E$) divided by an estimate on its stock estimate ($R$). It reflects the inverse of the number of years until the stock estimate is deployed at current extraction rates. This ratio is divided by the stock estimate to account for differences in stock size. Furthermore, the ADP is defined relative to the reference substance antimony[6] for which the same ratio is calculated. Equation 1 shows the calculation of the ADP (which is at the same

---

[4] UN Environment applied the following levels of recommendation: “strongly recommended”, “recommended”, ”interim recommended”, and “suggested or advisable”. The level of recommendation is determined based on the maturity of the methods, as identified by the following criteria: a) environmental relevance and scientific robustness, b) availability of data / extrapolation approaches within the domain of applicability, c) completeness, d) parsimony, e) documentation and transparency, f) testing, g) stakeholder acceptance and comprehensibility, and h) improvement relative to existing approaches.

[5] Equation 1 shows the universal ADP formula. The stock estimate may be represented by ultimate reserves (this section), economic reserves (next section) and other stock estimates.

[6] The choice of the reference substance was arbitrary (see Guinee et al. 1995).

time the characterisation factor (*CF*)) for a resource *i* relative to the reference substance antimony (*ref*). For $ADP_{UR}$ the stock estimate *R* is the ultimate reserve (crustal content).

$$ADP_i = CF_i = \frac{E_i/R_i}{E_{ref}/R_{ref}} * \frac{1/R_i}{1/R_{ref}} = \frac{E_i/R_i^2}{E_{ref}/R_{ref}^2} \quad (1)$$

The indicator result is expressed in kg antimony equivalents. This indicator is best fit to answer the question "How can I quantify the relative contribution of a product system to the depletion of resources?".

### 2.5.3 Abiotic Depletion Potential, economic reserves

The Abiotic Depletion Potential, economic reserves ($ADP_{ER}$) is based on the same equation (1) and relies on the economic reserves as the stock estimate *R*. The (economic) reserves are the part of known resources that is judged to be economically extractable at a given point in time. The extraction-to-stock ratio can be interpreted as a scarcity measure and accordingly the CFs of $ADP_{ER}$ as a measure of the pressure on the availability of primary mineral resources.

The indicator result is expressed in kg antimony equivalents.

This indicator is best fit to answer the question "How can I quantify potential resource availability issues for a product system related to physico-economic resource scarcity?".

### 2.5.4 Surplus Ore Potential, ultimate recoverable resource

The surplus ore potential (SOP) (Vieira et al. 2017) measures the average additional ore required to produce the resource in the future, based upon resource grade-tonnage distributions and the assumption that higher grade ores are preferentially extracted.

A log-logistic relationship between ore grades and cumulative extraction is developed for each resource 'x' based upon fitting regression factors ($\alpha_x$ and $\beta_x$) to the observed ($A_x$; $kg_x$) grade-tonnage distribution of deposits (see equation (2)). Prior to this procedure, an economic allocation of ore tonnage is performed to account for potential co-production. An average characterisation factor is developed by integrating along the product of resource extraction ($RE_x$) and the inverse of the grade log-logistic relationship ($OM_x$; the amount of ore mined per amount of resource x) from current cumulative resource extraction ($CRE_x$) to the maximum resource extraction (MREx) then dividing by total remaining extraction ($R_x$). Therefore, the CF representing the average surplus ore potential of each resource ($SOP_x$; the amount of ore extracted in $kg_{ore}$ per amount of resource extracted in $kg_x$) can be expressed as:

$$SOP_x = \frac{\int_{CRE_{x,total}}^{MRE_x} OM_x(RE_x)\, dRE_x}{R_x}, \text{ where } OM_x = \frac{1}{G_x} = \frac{1}{exp(\alpha_x)\left(\frac{A_{x,sample} - CRE_{x,sample}}{CRE_{x,sample}}\right)^{\beta_x}} \quad (2)$$

For the indicator $SOP_{URR}$ the total remaining extraction ($R_x$) is approximated with the ultimate recoverable resource (URR, approximated as 0.01% of the resource within 3 km under the surface).

This indicator is best fit to answer the question "How can I quantify the relative consequences of the contribution of a product system to changing resource quality?".

### 2.5.5 ESSENZ

The ESSENZ method (Bach et al. 2016), addresses 11 geopolitical and socio-economic accessibility constraints, in particular:

- country concentration of reserves and of mine production,
- price variation,
- co-production,
- political stability,
- demand growth,
- feasibility of exploration projects,
- company concentration,
- primary material use,
- mining capacity,
- trade barriers.

Indicators for these categories are determined and divided by a target threshold above which accessibility constraints are assumed to occur. Subsequently, this distance-to-target (DtT) value is normalised by the global production of the respective resource to consider that the accessibility constraints described above can be more severe for resources produced in relatively low amounts. Finally, the normalised DtT factors are scaled (to a range between 0 and $1.73 \times 10^{13}$ in each category). The aggregated characterisation factors offered as supplementary material to Frischknecht & Jolliet (ed.) (2019) are used in this study.

This indicator is dimensionless and thus has no particular meaning (despite that higher supply risks are represented by higher indicator values).

This indicator is best fit to answer the question “How can I quantify potential resource accessibility issues for a product system related to short-term geopolitical and socio-economic aspects?”.

# 3 LIFE CYCLE INVENTORY DATA

The data documented in the IEA PVPS Task 12 report T12-19:2020 (Frischknecht et al. 2020), serve as a basis for assessing the production, installation operation, dismantling and end of life (takeback and treatment/recycling) of the 3 kWp PV systems.

**Tab. 3.1 Key characteristics and key data of residential scale PV systems using mono-crystalline, multi-crystalline and CdTe panels, respectively (Frischknecht et al. 2020) [1]): Series 4, [2]): Series 6**

| | unit | mono-Si | multi-si | CdTe |
|---|---|---|---|---|
| **PV system** | | | | |
| Average annual yield over lifetime (linear degradation included) | kWh/kWp/a | 975 | | |
| Degradation (linear) | %/a | 0.7 | | |
| Lifetime of module | a | 30 | | |
| Lifetime of inverter | a | 15 | | |
| Module efficiency | % | 19.5 | 18 | 18 |
| Wafer thickness | µm | 170 | 180 | n.a. |
| Kerf loss | µm | 65 | | n.a. |
| Further losses | µm | 20.5 | 27.5 | n.a. |
| Glass thickness | mm | 3.2 | | 3.2+3.2 [1])<br>2.1+2.8 [2]) |
| **Supply chain** | | | | |
| Electricity consumption | | | | |
| - MG silicon | kWh/kg | 11 | | |
| - polysilicon production | kWh/kg | 49 | | n.a. |
| - CZ monocrystal / casting | kWh/kg | 32 | 7 | n.a. |
| - wafer manufacturing | $kWh/m^2$ | 4.8 | 5.6 | n.a. |
| - cell manufature | $kWh/m^2$ | 17.7 | | n.a. |
| - Panel manufacturing | $kWh/m^2$ | 14 | | 34 |

# 4 LIFE CYCLE IMPACT ASSESSMENT

## 4.1 Overview

This chapter contains the results of the resource use impacts assessed with the four indicators introduced in Subchapter 2.5. The results are discussed in more detail and separated by components and resources in Subchapters 4.2 to 4.6. Data quality and uncertainty are discussed in Subchapter 4.7.

Tab. 4.1 lists the resource use impacts of 1 kWh of electricity generation with different residential scale PV systems. The resource use impacts per kWh electricity produced with the three different technologies are rather similar.

**Tab. 4.1 Resource use impacts of generating 1 kWh of AC electricity quantified with four different resource indicators (see Subchapter 2.5 for a description of the resource use indicators)**

| per kWh AC electricity | | mono-Si | multi-Si | CdTe |
|---|---|---|---|---|
| Abiotic depletion potential, ultimate reserves | kg Sb eq | 5.29E-06 | 5.36E-06 | 5.26E-06 |
| Abiotic depletion potential, economic reserves | kg Sb eq | 1.04E-05 | 1.08E-05 | 1.21E-05 |
| Surplus ore potential, SOP | kg ore | 1.29E-02 | 1.32E-02 | 1.11E-02 |
| Essenz, aggregated | - | 1.15E+06 | 1.20E+06 | 9.59E+05 |

## 4.2 Cumulative resource extraction

The electricity production with residential PV systems requires the extraction of numerous metals and minerals (see Tab. 4.2). Gravel (and sand) needed in infrastructures (factories, roads) and in glass manufacture is used in largest amounts (between 8.5 and 11.6 grams per kWh) followed by aluminium (panel frame, 0.5 to 0.8 grams per kWh), iron (supporting structure, 0.5 to 0.6 grams per kWh) and copper (electric installations, about 0.2 grams per kWh). Some metals are used in distinctly smaller amounts such as gold (electronics in the inverter, about 0.07 mg per kWh), Silver (panel, 0.4 to 0.7 mg per kWh), and technology specific elements like cadmium and tellurium. The difference in tellurium intensity of the three panel systems is small. Note that the interpretation of **Tab. 4.2** should be within the framework of LCA and not directly interpreted as or compared to a bill of materials. While the bill of materials reports 2.24 mg Cd and 2.54 mg Te per kWh of AC electricity produced with a CdTe PV system, applying economic allocation in a life cycle assessment framework (International Organization for Standardization (ISO) 2006) yields the amounts or resources extracted shown in **Tab. 4.2**. Tellurium is co-extracted with silver and copper and the resource consumption is allocated based on economic relationships[7]. According to the inventory data and the allocation factors used, most of the tellurium extracted is linked to the silver supply chain.

**Tab. 4.2 Resource extraction quantified in mg metal and mineral caused by the generation of 1 kWh of AC electricity; The table shows a selection of the most relevant mineral and metal resources extracted.**

| Mineral resource | mono-Si PV system | multi-Si PV system | CdTe PV system |
|---|---|---|---|
| Gold | 0.07 | 0.07 | 0.07 |
| Silver | 0.67 | 0.71 | 0.39 |
| Copper | 195 | 196 | 180 |
| Aluminium | 651 | 698 | 497 |
| Molybdenum | 3.17 | 3.21 | 2.88 |
| Tin | 5.20 | 5.44 | 2.54 |
| Tellurium | 0.0048 | 0.0051 | 0.0056 |
| Zinc | 8.23 | 8.78 | 6.38 |
| Lead | 1.65 | 1.68 | 1.54 |
| Iron | 531 | 553 | 477 |
| Nickel | 9.35 | 9.63 | 8.20 |
| Chromium | 16.1 | 16.7 | 13.0 |
| Cadmium | 0.00 | 0.00 | 2.24 |
| Palladium | 0.0003 | 0.0003 | 0.0003 |
| Magnesium | 8.93 | 9.67 | 1.57 |
| TiO2 | 7.49 | 8.21 | 1.30 |
| Gravel | 9 922 | 10 075 | 8 504 |
| Sulfur | 2.87 | 2.94 | 2.35 |

## 4.3 Abiotic Resource Depletion Potential, ultimate reserves, $ADP_{UR}$

The resource depletion impact quantified with $ADP_{UR}$ amounts to between 5.3 and 5.4 mg Sb-eq/kWh AC electricity (Tab. 4.1, Fig. 4.1 and Fig. 4.2). The resource use of the inverter contributes between 80 and 92 % of the total score, followed by the panel (15 %, 16 % and 14.5 % of mono-Si, multi-Si and CdTe PV systems, respectively). The balance of system contributes about 4 % to the resource depletion impact. Remaining construction efforts, operation and end of life treatment are hardly visible.

[7] See Appendix A for a quantitative description of parts of the supply chain of tellurium.

Gold, silver, copper, tellurium and cadmium are the most important resources, contributing 95 to 98 % to the resource depletion impact.

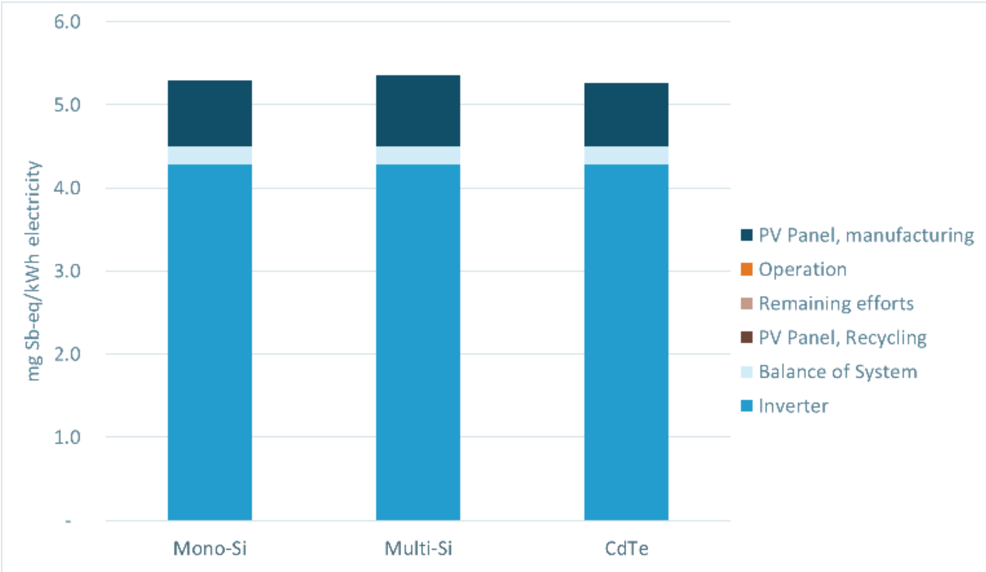


**Fig. 4.1 Resource depletion impacts, quantified with the Abiotic Depletion Potential, ultimate reserves, in mg Sb-eq per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of life cycle stages and PV system components average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

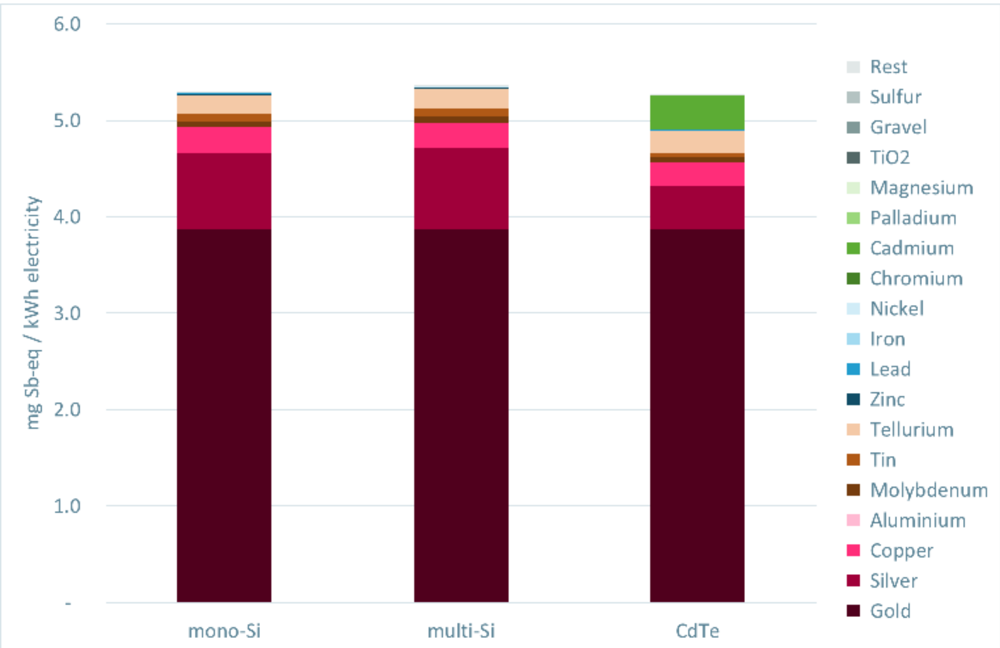


**Fig. 4.2 Resource depletion impacts, quantified with the Abiotic Depletion Potential, ultimate reserves, in mg Sb-eq per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of main metals and minerals average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

## 4.4 Abiotic Resource Depletion Potential, economic reserves, $ADP_{ER}$

The resource scarcity impact quantified with $ADP_{ER}$ amounts to between 10 mg Sb-eq (crystalline silicon PV systems) and 12 mg Sb-eq (CdTe PV system) per kWh AC electricity (Tab. 4.1, Fig. 4.3 and Fig. 4.4). The resource use of the inverter contributes between 43 % and 50 % of the total score and the panel between 45 % and 42 % (crystalline and CdTe PV systems, respectively). The balance of system contributes about 7 to 8 % to the resource scarcity impact. Remaining construction efforts, operation and end of life treatment are hardly visible.

Silver, gold, copper, molybdenum, tin, and cadmium (CdTe PV system only) are the resources contributing to more than 95 % of the resource scarcity impacts.

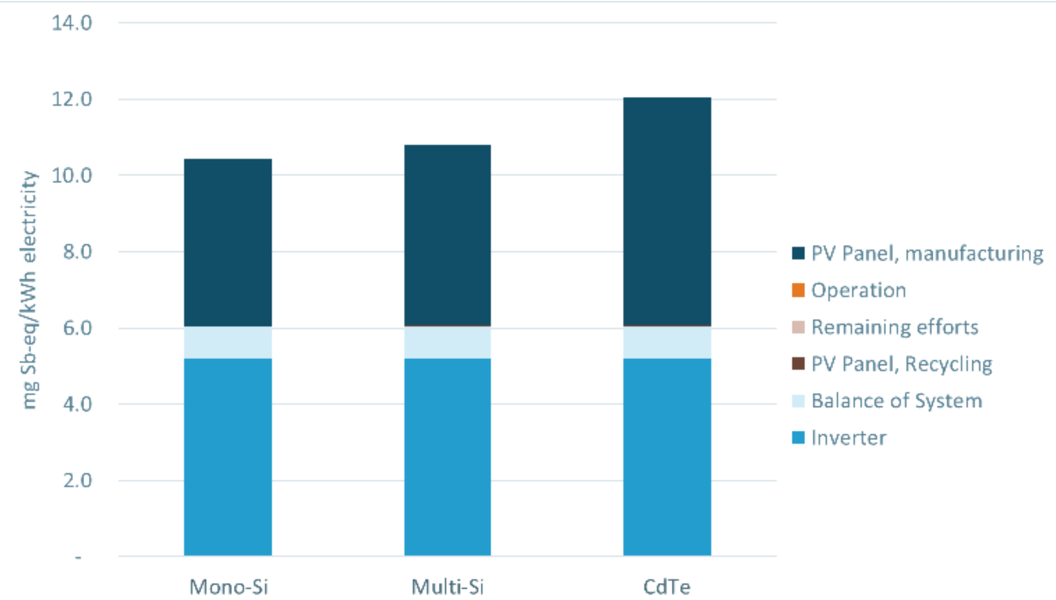


**Fig. 4.3 Economic resource scarcity impacts, quantified with the Abiotic Depletion Potential, economic reserves, in mg Sb-eq per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of life cycle stages and PV system components average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

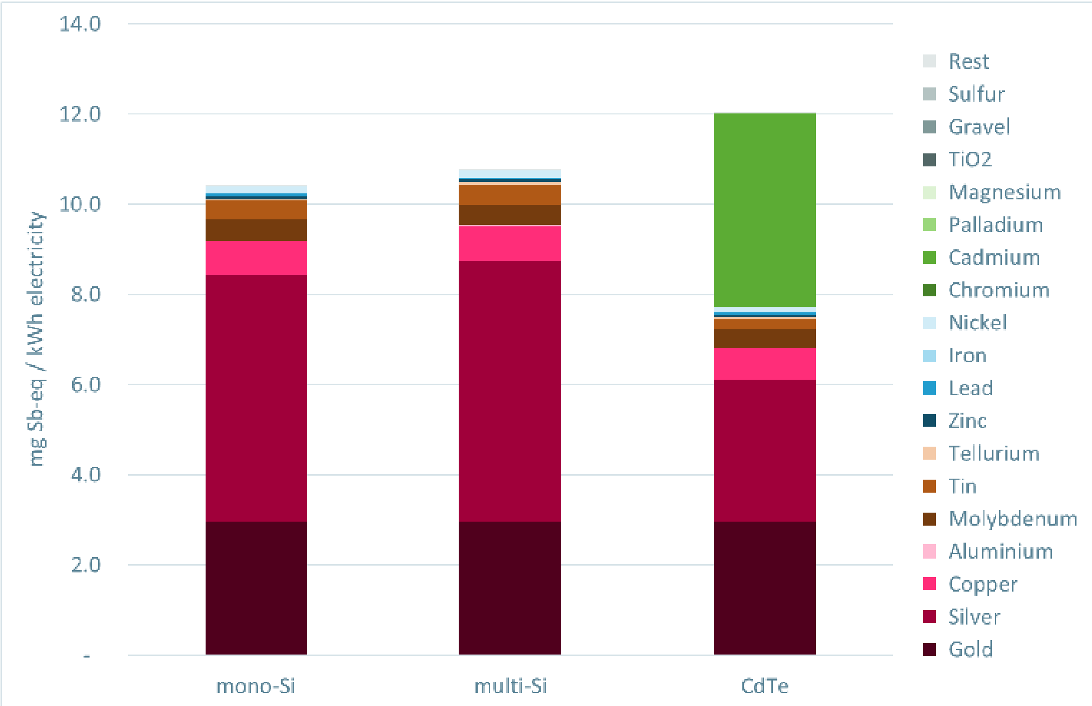


**Fig. 4.4 Economic resource scarcity impacts, quantified with the Abiotic Depletion Potential, economic reserves, in mg Sb-eq per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of main metals and minerals average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

## 4.5 Surplus Ore Potential, SOP

The resource quality impact quantified with $SOP_{URR}$ amounts to between 11 100 mg and 13 200 mg ore per kWh AC electricity (Tab. 4.1, Fig. 4.5 and Fig. 4.6). The resource use of the inverter contributes between 44 % and 57 % of the total score and the balance of system between 29 % and 36 %. The PV panel contributes 7 % (CdTe) and between 21 % and 27 % to the total resource quality impact. Remaining construction efforts, operation and end of life treatment are negligible.

Gold, copper, aluminium, silver, molybdenum, iron and nickel are the resources contributing to more than 95 % of the total resource quality impacts of crystalline silicon and CdTe PV systems.

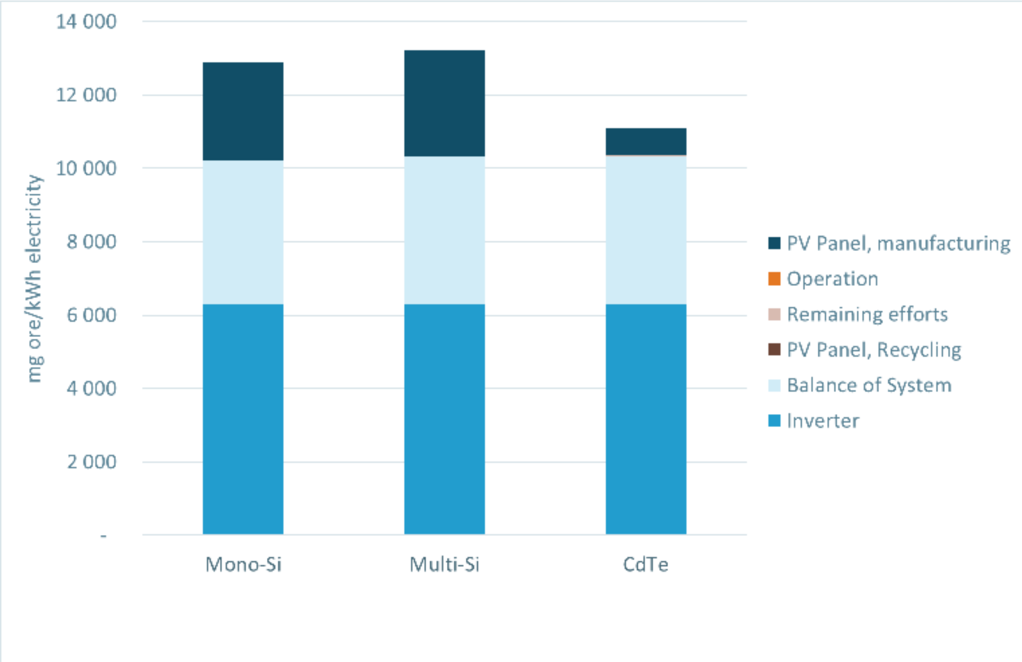


**Fig. 4.5 Resource quality impacts, quantified with the Surplus Ore Potential, ultimate recoverable resources, in mg ore per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of life cycle stages and PV system components average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

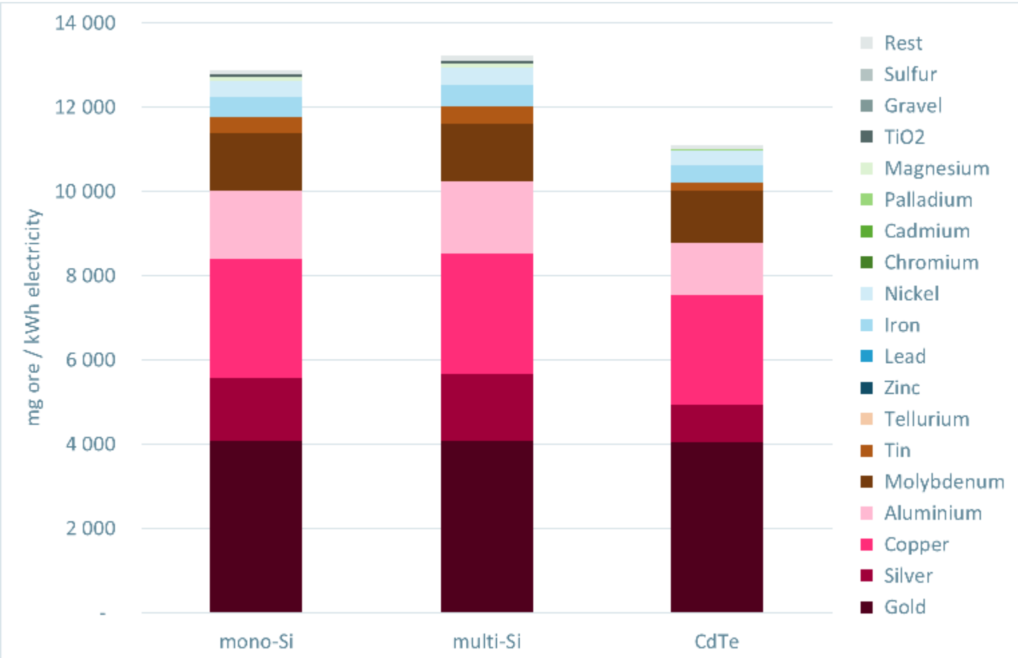


**Fig. 4.6 Resource quality impacts, quantified with the Surplus Ore Potential, ultimate recoverable resources, in mg ore per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of main metals and minerals average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

## 4.6 Resource criticality, ESSENZ

The resource criticality impact quantified with ESSENZ[8] amounts to between 1 000 000 and 1 200 000 per kWh AC electricity produced with crystalline silicon and CdTe PV systems (Tab. 4.1, Fig. 4.7 and Fig. 4.8). The resource use of the inverter contributes between 38 % and 47 % of the total score and the panel between 35 % and 49 % (crystalline and CdTe PV systems). The balance of system contributes 13 % (crystalline silicon) and 16 % (CdTe) to the total resource criticality impact. Remaining construction efforts, operation and end of life treatment are negligible.

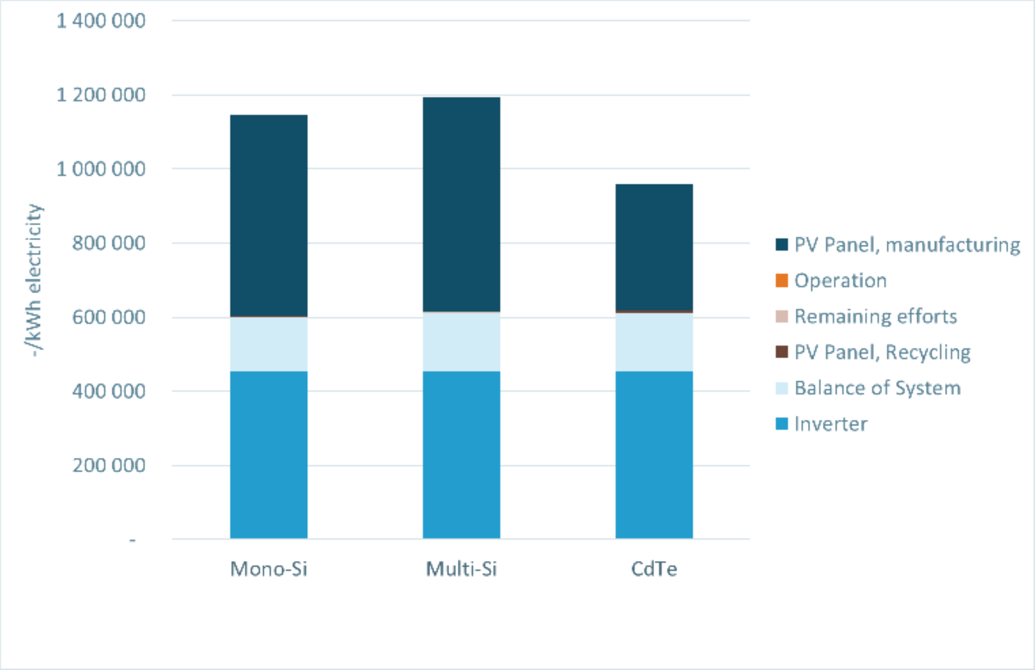


**Fig. 4.7 Resource criticality impacts, quantified with ESSENZ, expressed in dimensionless scores per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of life cycle stages and PV system components average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

Tellurium, gravel, gold, aluminium, silver, tin, molybdenum, nickel and palladium are the resources contributing to more than 95 % of the total resource criticality impact of crystalline silicon and CdTe PV systems.

---

[8] ESSENZ uses dimensionless scores.

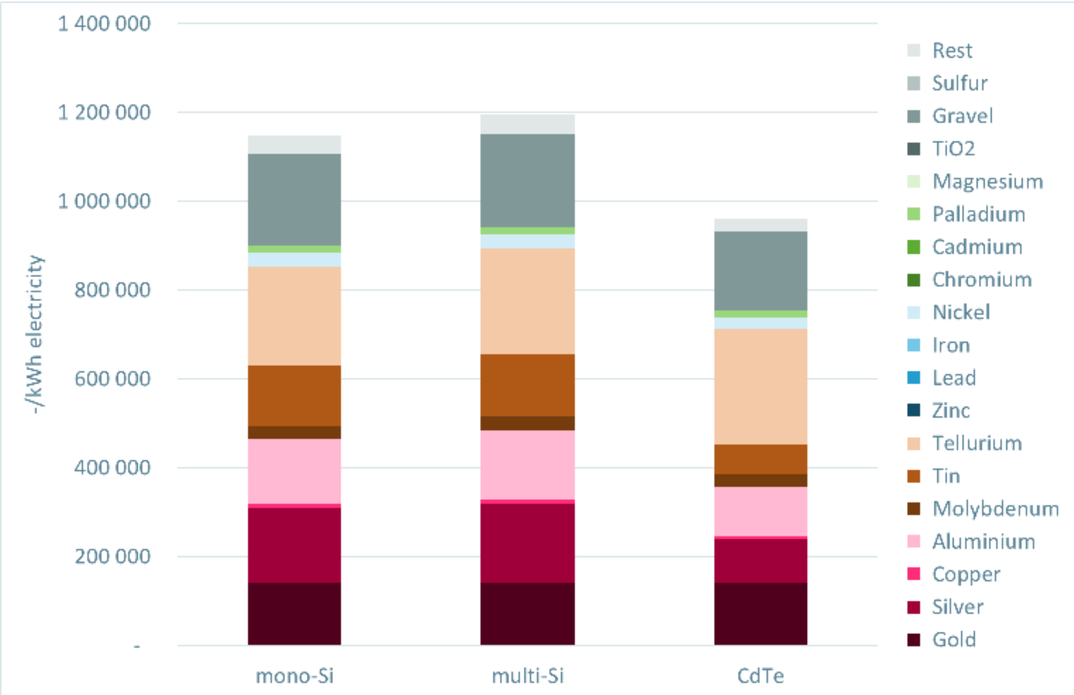


**Fig. 4.8 Resource criticality impacts, quantified with ESSENZ, expressed in a dimensionless number per kWh AC electricity produced with residential scale PV systems operated in central Europe; contribution of main metals and minerals average annual yield over lifetime: 975 kWh/kWp (incl. linear degradation of 0.7 % per year); panel lifetime: 30 years; inverter lifetime: 15 years.**

## 4.7 Data quality and uncertainty

This life cycle inventory analysis is based on current data on the bill of materials and the supply chain of the different panel technologies. The data on mounting structures is less recent but considered appropriate for the resource assessments documented and discussed in this report.

Life cycle inventory data on inverters have been updated recently. Life cycle inventory data of the electronic components used in the inverters are rather aged and may be a source of larger uncertainties in those cases where resources such as gold or tellurium contribute substantially to the cumulative resource use impact.

The resource use impacts are quantified based on the resources extracted because the life cycle inventories available do not yet systematically quantify the amounts of metals and minerals lost (disperse emissions, in landfills and in waste incineration).

The recycling of cadmium and tellurium when treating CdTe panels may contribute to the reduction of the resource depletion ($ADP_{UR}$) and the resource scarcity ($ADP_{ER}$) impact of electricity produced with those panels. The recycling of the aluminium frame may contribute to reducing the resource quality ($SOP_{URR}$) impact. Finally, the recovery of gold during treatment and recycling of the inverter may help reducing the resource use impact quantified with any of the four resource use indicators applied in this analysis.

To that end, the recovery rates of the metals and minerals mentioned before need to be known. This would allow to determine the share of metals and minerals used dissipatively and thus lost to the environment (Berger 2020; Frischknecht 2014; Sonderegger et al. 2020).

# 5 CONCLUSIONS AND OUTLOOK

This work reports, for the first time, the resource use impacts of electricity generated by residential PV systems quantified with four different resource use indicators. These indicators address distinctly different aspects of resource use, namely resource depletion ($ADP_{UR}$), economic resource scarcity ($ADP_{ER}$), resource quality ($SOP_{URR}$) and resource criticality (ESSENZ), based on the same LCI data and model. The assessment and the results provide answers to different questions related to resource use. Hence, it is recommended to identify the indicator most suited to answer the associated resource question at hand (e.g., be it resource depletion or rather resource criticality) and then to use the results of the appropriate indicator. A simultaneous use and application of all four indicators is discouraged.

The assessment and the results described in this report show resource use impacts per kWh and aggregate metal and mineral resources according to different perspectives. They thus differ from those of resource use considerations published for instance by IEA (2021). In that report world demand of selected individual critical metals and minerals per power generation technology (solar PV: copper, silicon, and silver) and the effect of technology shifts on those and other metals and minerals are forecasted.

The total mineral and metal extraction per kWh for residential European PV electricity ranges between 16 and 20 grams. More than 85 % of the total mass of minerals and metals are sand, gravel, clay, and calcite (used in infrastructures and in glass making), 4 % copper, 3 to 4 % aluminium, and 3 % iron.

Resource use impacts on resource depletion and on resource quality are similar for all three PV technologies. Less than ten minerals and metals contribute to at least 95 % of the overall score of all four resource use impact indicators. Gold, silver and copper are always in the top ten minerals and metals. While gold is mainly used in the inverter electronics and copper in the cabling and in the inverter, silver is mainly used in crystalline silicon panels and in the inverter electronics.

Tellurium (CdTe panel and inverter electronics), tin (inverter electronics) as well as gravel and sand (infrastructures and panel glass) are important substances regarding resource criticality (ESSENZ).

The inverter often contributes most to the resource use impacts followed by the PV panel. The alloying elements used in the supporting structure contribute significantly to the surplus ore potential (SOP).

The study contributes to better understand the various and multi-facetted resource use impacts of different PV systems. The study helps readers to choose the resource use indicator appropriate for their question or concern. The results help to identify which metals and/or minerals could be targets for reduction in use (increase material efficiency) and for increase in resource recovery during end-of-life treatment. Depending on the indicator (and on the resource use related question at stake) this may be different metals and/or minerals.

Information and data on the share of minerals and metals recovered during collection, treatment and recycling of panels, inverters, cabling and supporting structures would allow to quantify the impacts on depletion, scarcity, quality, and criticality of consumptive resource use. This information and data should be collected for metals and minerals contributing significantly to resource use impacts including gold, silver, copper, tellurium and tin, and the respective life cycle inventory datasets should be complemented accordingly.

Future research should establish recovery rates of the most important minerals and metals achieved and achievable in commercially operated recycling facilities of crystalline silicon, CIS and CdTe panels as well as inverters and electric installations. Such information should then be embedded in the life cycle inventories of PV systems and their supply chains.

# REFERENCES

Bach V., Berger M., Henßler M., Kirchner M., Leiser S., Mohr L., Rother E., Ruhland K., Schneider L., Tikana L. and Volkhausen W. (2016) Integrated method to assess resource efficiency – ESSENZ. *In: J Clean Prod*, **137**, pp. 118–130, 10.1016/j.jclepro.2016.07.077.

Berger M., Sonderegger, T., Alvarenga, R., Bach, V., Cimprich, A., Dewulf, J., Frischknecht, R., Guinée, J., Helbig, C., Huppertz, T., Jolliet, O., Motoshita, M., Northey, S., Peña, C.A., Rugani, B., Sahnoune, A., Schrijvers, D., Schulze, R., Sonnemann, G., Valero, A., Weidema, B.P. & Young, S.B. (2020) Mineral resources in life cycle impact assessment: part II – recommendations on application-dependent use of existing methods and on future method development needs. *In: International Journal of Life Cycle Assessment*, **25**(4), pp. 798-813.

Classen M., Althaus H.-J., Blaser S., Doka G., Jungbluth N. and Tuchschmid M. (2009) Life Cycle Inventories of Metals. ecoinvent report No. 10, v2.1. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, CH, retrieved from: www.ecoinvent.org.

Frischknecht R. (2014) Impact assessment of abiotic resources: the role of borrowing and dissipative resource use. *In proceedings from: LCA Forum No. 55*, 11. April 2014, Zürich, LCA Forum Society.

Frischknecht R. and Jolliet O. (ed.) (2016) Global Guidance on Environmental Life Cycle Impact Assessment Indicators, Volume 1. United Nations Environment Programme, UNEP, Paris.

Frischknecht R. and Jolliet O. (ed.) (2019) Global Guidance on Environmental Life Cycle Impact Assessment Indicators, Volume 2. United Nations Environment Programme, UNEP, Paris.

Frischknecht R., Stolz P., Krebs L., de Wild-Scholten M., Sinha P. and Raugei M. (2020) Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems, Report T12-19:2020. International Energy Agency (IEA) PVPS Task 12.

IEA (2021) The Role of Critical Minerals in Clean Energy Transitions; World Energy Outlook Special Report International Energy Agency, Paris, France.

International Organization for Standardization (ISO) (2006) Environmental management - Life cycle assessment - Requirements and guidelines. ISO 14044:2006; First edition 2006-07-01, Geneva, Switzerland.

KBOB, ecobau and IPB (2022) UVEK Ökobilanzdatenbestand DQRv2:2022. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: www.lc-inventories.ch.

Mela G., Carvalho M. L., Temporelli A. and Pierpaolo G. (2021) The Commodity Life Cycle Costing Indicator. An Economic Measure of Natural Resource Use in the Life Cycle. *In: Sustainability*, **13**(9), pp., https://doi.org/10.3390/su13094870.

Sonderegger T., Berger M., Alvarenga R., Bach V., Cimprich A., Dewulf J., Drielsma J., Frischknecht R., Guinée J., Helbig C., Huppertz T., Jolliet O., Motoshita M., Northey S., Rugani B., Schrijvers D., Schulze R., Sonnemann G., Thorenz A., Valero A., Weidema B. P. and Young S. B. (2020) Mineral resources in Life Cycle Impact Assessment part I: a review. *In: Int. J. Life Cycle Assessment*, **25**, pp. 784–797.

Stolz P., Frischknecht R., Wambach K. and Heath G. (2016) Life cycle assessment of the current generation recycling of c-Si and CdTe PV modules. *In proceedings from: 32nd EU PVSEC*, Munich, retrieved from: www.photovoltaic-conference.com.

TS PEF Pilot PV (2019) Product Environmental Footprint Category Rules (PEFCR): Photovoltaic Modules used in Photovoltaic Power Systems for Electricity Generation. treeze Ltd., commissioned by the Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation", Uster, Switzerland.

Tuchschmid M. and Classen M. (2009) Semiconductors: Tellurium, Gallium and Cadmium Compounds. In: *Life Cycle Inventories of Metals,* Vol. 10 (Ed. Classen M., Althaus H.-J., Blaser S., Doka G., Jungbluth N. and Tuchschmid M.). ecoinvent Centre, Uster and Dübendorf, Switzerland.

Vieira M., Ponsioen T. C., Goedkoop M. J. and Huijbregts M. A. J. (2017) Surplus Ore Potential as a Scarcity Indicator for Resource Extraction. *In: Journal of Industrial Ecology*, **21**(2), pp. 381-390, DOI: 10.1111/jiec.12444.

# A APPENDIX: SUPPLY CHAIN OF TELLURIUM

According to the corresponding LCI report (Classen et al. 2009), most of tellurium is co-produced with copper and silver. Silver and tellurium are present in an anode slime which is further processed to a cement.

The responsible authors of the LCI documentation on tellurium (Tuchschmid & Classen 2009) performed an economic allocation which leads to the following life cycle based specific amounts of tellurium extracted from the ground (annual production volumes of silver and tellurium in combined mines in brackets) when supplying 1 kg of each of the three elements (Ag and Te):

- 1 kg silver, from copper production (4 875 t): 0.022 kg Te
- 1 kg tellurium, semiconductor grade (107.6 t): 0.001722 kg Te

The supply of 1 kg silver co-produced with copper causes the extraction of 22 g of tellurium. Similarly, the supply of 1 kg tellurium recovered from anode slimes generated when extracting copper and silver causes the extraction of 1.72 g of tellurium.

The main share (>99 %) of the 107.6t of tellurium extracted annually is booked via the silver supply chain.

Technology Collaboration Programme
by iea

ISBN 978-3-907281-25-3