Germanium wafers for high concentration photovoltaics: exergetic resource consumption.

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Abstract The goal of the study was to determine the resource consumption of the production of germanium wafers and to relate it to the possible resource savings by their application in high concentration photovoltaic systems. The material and energetic requirements for a current production of germanium wafers have been inventoried and converted to cumulative exergy requirements. The results showed a Cumulative Exergy Extraction from the Natural Environment (CEENE) of 258 MJex per four inch wafer. This data has been used to determine a partial exergy payback time of germanium wafers used in a high concentration photovoltaic system installed in the south-west of the USA. As lenses, concentrating the sunlight, are applied in the photovoltaic system, the amount of semi-conductor material required is reduced. The calculated partial exergy payback time was 4.2 days. Comparing the results to reported energy payback times of complete systems indicated that the germanium wafer accounts for less than 5% of the overall resource consumption for a complete system. To study the variability of the results one parameter with respect to the location of germanium wafer production and two parameters with respect to the location of installation of the photovoltaic system have been changed. In case of location of production the resource profile of the electricity input to germanium wafer production and important upstream processes has been adapted. In case of location of installation direct normal irradiation (DNI) and the profile of the substituted electricity have been adapted according to country and/or region. This showed that the location of germanium wafer production and of installation of the photovoltaic system both have a considerable impact on partial exergy payback times.

1 Introduction

Energy production more and more switches to renewable energy sources. Harvesting this energy however relies on the input of non-renewable resources. This is also the case for solar energy: Semi-conductor material is required to convert solar energy to electricity. For terrestrial applications silicon-based technology is mostly employed. However, high efficiency multi-junction solar cells with germanium as substrate are advocated as an alternative, provided that the use of the costly semi-conductor material is minimised by employing mirrors or lenses to concentrate the sunlight. This is what is done in high concentration photovoltaic (HCPV) systems. In the following the resource input required for the production of germanium wafers will be quantified and related to the resource savings generated by the electricity production of an HCPV system.

2 Materials and Methods.

The germanium wafer production has been inventoried based on data provided by Umicore for their wafer production process in Quapaw (USA). Germanium for the production of germanium wafers can be won from residues of zinc refining [1]. These residues need to be processed further, before they can be used as an input to the germanium wafer production. Data for this refining process was provided by Umicore as well. For the quantification of processes taking place upstream of Umicore, for example the electricity production, datasets from the ecoinvent database (v2.1) [2] have been used.

The resource requirement of the process has been determined in terms of the Cumulative Exergy Extraction from the Natural Environment (CEENE) [3]. Using exergy for the quantification of resources has the advantage that exergy measures not only the quantity but also the quality of energy. Furthermore, the CEENE method quantifies the amount of exergy of which the natural environment has been deprived due to an industrial production process. By grouping natural resources in a number of categories - renewable resources (non biomass), fossil fuels, nuclear energy, metal ores, minerals and mineral aggregates, water resources, land occupation and transformation (incl. land use for biomass production) and atmospheric resources - a resource use fingerprint of the production process can be obtained.

To relate the CEENE value of the germanium wafer production to the resource savings due to electricity production of an HCPV system, the partial exergy payback time (ExPT) has been defined as the ratio between CEENE for the germanium wafer production to CEENE for the production of the replaced electricity. The HCPV electricity production was modelled based on a system produced by Concentrix Solar [4]. The system employs lenses and a two-axis tracker to assure optimal use of the direct solar irradiation. The amount of required germanium wafers per system has been verified via personal communication with Concentrix Solar. For the resource savings due to electricity production with solar energy, it has been assumed that the electricity replaces fossil and nuclear based electricity production. In contrast to conventional PV system, HCPV systems can only make use of direct normal irradiation (DNI). The required irradiation data was estimated from [5].

3 Results and Discussion

3.1 Germanium wafer production

In the germanium wafer production process germanium dioxide from the residue processing is further purified in chlorination and hydrolysis steps. High purity germanium is obtained during zone refining. A germanium crystal is produced via the Czochralski process. Subsequently, the germanium wafer is manufactured via several cutting, grinding, and etching steps. Before leaving the facility, the wafers are cleaned and undergo inspection. A number of supportive processes, mainly aimed at recycling germanium wastes produced at several points in the process network, have also been included in the assessment.

The overall resource extraction for the production of one germanium wafer equals 258 MJex in terms of CEENE when production is assumed to take place in the USA. Figure 1 represents the inputs to the different process steps expressed in CEENE. It can be observed that the germanium dioxide material input to the process is a major contributor to the overall resource consumption. Other important inputs are due to high electricity usage during zone refining and the germanium crystal growth. As electricity is an important input to the germanium wafer production process and also to a number of upstream processes like acid production, the impact of the electricity mix on the fingerprint of the germanium wafer production has been examined (figure 2). To this end the mix of the direct electricity input and the major indirect electricity inputs has been varied according to the electricity mixes of a number of countries, most of them European. The resulting overall CEENE values range from 155 MJex for the Norwegian electricity mix to 308 MJex for the Greek electricity mix. The CEENE fingerprint of the germanium wafer production varies considerably with the profile of the assumed electricity input. This is exemplified by the high share of nuclear resources for the French case, the high land use for the Finnish case (biomass) or high value for renewable resources for Norway (hydropower).

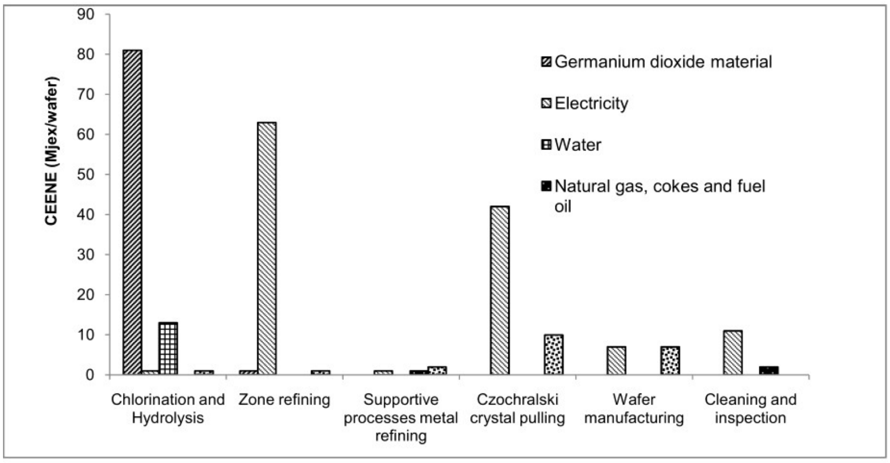
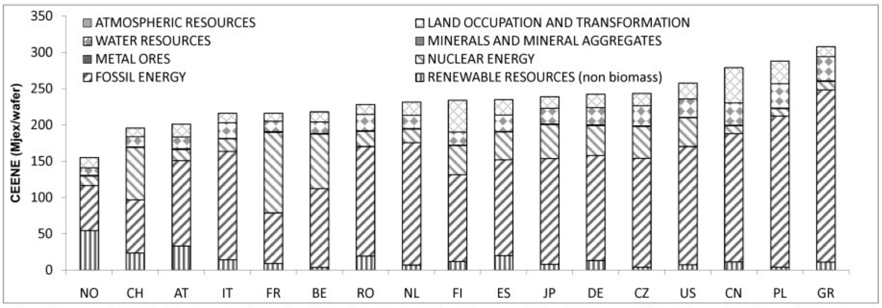


Fig.1: CEENE results for the production of one germanium wafer.



NO = Norway, CH=Switzerland, AT = Austria , IT = Italy, FR = France, BE = Belgium, RO = Romania, NL = Netherlands, FI = Finland, ES = Spain, JP = Japan, DE = Germany, CZ = Czech Republic, US = United States of America, CN = China, PL = Poland, GR = Greece

Fig.2: Variation of the CEENE fingerprint of the germanium wafer production in function of the electricity mix used in the production itself and the most important upstream processes.

3.2 Partial exergy payback time

In a first instance, it was assumed that the HCPV system is installed in the south-west of the USA. Thus the annual DNI was determined as 2500 kWh/m². For the CEENE value of the electricity production from fossil fuel and nuclear resources in the USA, a value of 15.4 MJex/kWh was obtained. Based on these assumptions a partial ExPT of 4.2 days was calculated. The low value can be attributed to the relative small amount of wafers required for an HCPV system.

In order to judge the share of the germanium wafer in the overall resource consumption of an HCPV system, the calculated partial ExPT was compared to reported energy payback times, which range from a couple of months to more than one year [6-8]. Though CEENE values differ somewhat from primary energy values, because the CEENE method includes additional resources, employs different system boundaries and of course uses exergy instead of energy, it can be concluded that the germanium wafer contributes less than 5% to the overall resource consumption of such a system.

The amount of available DNI is a major factor for the potential electricity production of the HCPV system and can vary substantially between locations. In northern Europe the DNI hardly exceeds 1000 kWh/m².y, whereas it can reach more than 2500 kWh/m².y in the regions around 30° north or south of the equator. Next to the DNI the fingerprint of the replaced electricity production also depends on the location of the HCPV system. As a result choosing another location also has an effect on the partial ExPT of the germanium wafer. This is exemplified by the results represented in figure 3, which shows that the partial ExPT changes considerably with location, ranging from 3.5 to 15 days. Differences in the local electricity production technology cause a spread of the partial ExPT for the same DNI.

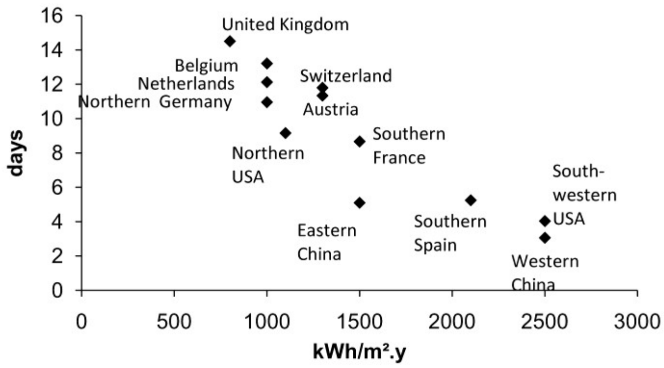


Fig.3: Variation of partial ExPT of germanium wafers used in HCPV system depending on location of installation, plotted in function of annual DNI.

4 Conclusions

The resource consumption for the production of germanium wafers for HCPV applications has been quantified. The fingerprint of the resource consumption is determined by the production process itself, but also by the sources of the required inputs. As concentrating the sunlight reduces the amount of germanium wafer required for an HCPV system, the germanium wafer's contribution to the overall resource consumption of such a system is small. The optimal location for installing an HCPV system depends on DNI, but also on the fingerprint of the local electricity production that will be replaced.

5 Acknowledgements

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6 References

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