ABSTRACT: As part of the Energy Strategy 2050, the electricity gap resulting from the phase-out of nuclear energy is primarily compensated with PV modules. The Energy Strategy 2050 plans the expansion of photovoltaics to 12 TWh in 2050. This could rise to 24 TWh due to the elimination of deep geothermal energy (4TWh) and the replacement of cars with combustion engines by electric vehicles (approx. 8TWh)\(^1\). Based on the current PV market, a huge number of installed PV modules will be seen 2050. These modules can be made up of different technologies such as c-Si, thin-film modules such as CdTe, CIS or CIGS. Assuming a service life of 25-40 years\(^2\), all these modules must be dismantled and disposed of again. Even for PV modules alone the quantities of material that will be disposed of in Switzerland and thus the recycled material flows are considerable. Forward-looking planning of the products employed, and their recycling is important for users and installers. This is where the joint research efforts of SENS eRecycling and the Bern University of Applied Sciences BFH come in.

Keywords: Recycling, power-weight ratio, life cycle

1 INITIAL POSITION

2.1 Brief introduction to the development of photovoltaics in Switzerland

In Switzerland, PV modules have been used for autonomous power supplies since the 1980s\(^3\). At that time, the PV systems had small PV capacity, i.e. less than one kWp installed. In 1981, the first two grid-connected PV systems were built in Switzerland and Europe (1.2 kWp Swiss Federal Institute for Reactor Research EIR and 10 kWp SUPSI Lugano). Around 1986, further grid-connected PV systems were installed in Switzerland\(^4\). The Tour de Sol in 1987 established a new participant category for "solar vehicles with grid-connected PV systems". This led to the construction of private, grid-connected PV systems in Switzerland. Around 1990, Switzerland was the world leader in the construction of decentralised grid-connected PV systems. However, the installed volumes were less than 1 MWp per year.

2.2 Disposal of PV modules in Switzerland: SENS eRecycling Foundation

With a lifetime of the PV modules of 25-40 years or more, it is to be expected that they will have to be dismantled again in the next few years. In addition, there are cases of fire and guarantee cases in which the modules need to be dismantled prematurely. In concrete terms, the following quantities have been recycled since 2015\(^5\):

- 2015: 71 tons
- 2016: 126 tons
- 2017: 337 tons

The strong increase in 2017 is astonishing and is primarily due to a warranty recall of a roof-integrated, frameless PV product. A few tons may also be due to disposal after a fire. PV modules that are installed on a building that is set on fire (usually not because of the PV system) usually lose their warranty and are recycled\(^6\).

The PV modules sent for recycling are accepted by the SENS eRecycling Foundation, the Swiss recycling organisation. SENS\(^1\) is a non-profit organisation founded in 1990 and responsible for the disposal and recycling of electrical waste in Switzerland. The legal framework is the "Ordinance on the Return and Disposal of Electrical and Electronic Equipment (VREG)" of 1 July 1998 (currently under revision). It contains a return obligation for consumers and a take-back obligation for manufacturers, importers and dealers. The costs are covered by the advance disposal fee, which roughly corresponds to the costs of recycling. The recovered material can be recycled to approximately 80% of the market value of the primary material.

The SENS eRecycling network includes manufacturers, importers and wholesalers. Partners and associations ensure coordination. For solar components it is Swissolar, the association of solar entrepreneurs in Switzerland. Recyclers are responsible for the effective processing of the equipment and components disposed of.

2.3 Recyclable material components of PV modules and their further processing

PV modules consist mainly of a cover glass, the embedding material for the interconnected solar cells (standard: 60/72 cells), the embedding material on the back and the foils to protect the solar cells. In most cases, an aluminium frame provides the mechanical stability and a junction box with diodes and two copper cables with plugs ensure the connection to power supply (Fig. 1). Recycling is therefore not very complicated.
Figure 1: MSX 64 polycrystalline PV module from Solarex (USA) with solid aluminium frame construction, a total weight of 7.2 kg and a large junction box. It is one of the best-selling PV modules from 1988-1998. This module was also very frequently deployed in Switzerland.

Depending on the technology, PV modules need to be recycled separately. All module types used in Switzerland are collected and recycled by the SENS eRecycling Foundation. Crystalline silicon is the dominant type recycled by SENS eRecycling as crystalline SI modules (c-Si) are being the technology primarily used in Switzerland. Modules with cadmium telluride technologies (Cd/Te) are hardly used in Switzerland (<1%). The market leader in this technology (First Solar), which does not sell any modules in Switzerland, has its own disposal line. Copper indium selenide (CIS) / copper indium gallium selenide (CIGS) modules are rarely used in Switzerland and only seen on PV facades.

The shares of materials used in PV modules disposed of by SENS eRecycling in Switzerland include the following materials:

- Glass (including silicon wafers): 88%.
- Metal (especially aluminium): 6%.
- Plastics (foils): 6%.

The aluminium frame is separated and directly transferred to aluminium recycling. The glass is either processed into flat glass or into glass wool and used as insulation material on construction sites. The PV laminate is mechanically shredded in a hammer mill. The particles are mechanically separated in:

- Ferrous metals (screws etc.)
- Non-ferrous metals (e.g. copper)
- Plastics
- Further extraneous materials.

The plastics are either used as substitute fuel in the cement industry or incinerated in a waste incineration plant (energy and heat generation).

All the processes described above are carried out in two factories in Germany, since the current quantities do not justify an own recycling plant in Switzerland. This means additional transports are required. The analysis of energy expenditure shows energy expenditure for transport is not significant using large quantities and applying a thought-out choice of means of transport. This even applies for PV modules originating in China or the Far East.

It is conceivable to separate the individual components more precisely and thus increase value creation in the future. It is perceived rather critically (personal communication by Roman Eppenberger, 29.5.2018) whether this could happen in Switzerland as the primary glass produced has little economic value. If silicon could be collected and recycled separately, this added value could improve, which is currently being investigated in various research projects. If chemical separation processes happen to be necessary for this, approval for the process could be a hurdle in Switzerland.

2 FUTURE OF RECYCLING PV MODULES

2.1 Improvements of material

In the future, only half of the material used per kWp of power output will have to be disposed of (Fig. 2; Fig. 3a, 3b). Over the past 40 years PV modules have become larger and more powerful. For example, the power-to-weight ratio of the MSX 64 PV module from Solarex (USA) shown in Fig. 1, with 112.5 kg per 1 kWp, has been halved by today’s technology. In some cases, the power output of PV modules has increased 10-fold from approx. 30 Wp to over 300 Wp.

Figure 2: The development of PV modules since 1985 shows the continuous increase in output over the past 30 years.

On the other hand, the efficiency has doubled: Today, a standard module has dimensions of approx. 1x1.6 m. The power-to-weight ratio, i.e. the material quantity for a standard output of 1 Wp, has almost halved. This means that only half as much material needs to be used for a kWh electricity yield as a list of PV modules from the last 30 years shows (Fig. 3a, 3b).
Due to the better sensitivity of the solar cells, also the yield per kWp is somewhat higher today. However, this effect is not very pronounced. The longer service life is likely to carry more weight. The fact that old PV modules such as MSX 64 from Solarex (see Fig. 1), KC 50 from Kyocera and first of all M55 from Arco Solar/Siemens last a very long time. This has been demonstrated by long-term PV module measurements by the PV laboratory of BFH. Longevity for new PV modules, has yet to be demonstrated. It is theoretically possible that price pressure could lead to a reduced service life and quality problems.

**Table I:** Calculated (*) and estimated (**) annually installed PV module volume in Switzerland of 2000-2025.

<table>
<thead>
<tr>
<th>Year</th>
<th>Market/Year</th>
<th>Quantity of material (to/year)</th>
<th>Dominant technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000**</td>
<td>1 MWp</td>
<td>100 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
<tr>
<td>2005*</td>
<td>5 MWp</td>
<td>400 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
<tr>
<td>2010*</td>
<td>30 MWp</td>
<td>2'100 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
<tr>
<td>2015*</td>
<td>300 MWp</td>
<td>18'000 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
<tr>
<td>2020**</td>
<td>500 MWp</td>
<td>25'000 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
<tr>
<td>2025**</td>
<td>1'000 MWp</td>
<td>50'000 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
</tbody>
</table>

* Calculation by Muntwyler (based on PV market figures) ** forecast by U. Muntwyler.

The expected cumulative material stock in 2050 (Energy Strategy 2050) is potentially much lower, as a further improvement of the power-to-weight ratio of 20% (40 kg/1 kWp) and an unchanged design of the PV modules can be assumed (Table 2).

**Table II:** The installed PV material quantities expected in 2050 (**forecast U. Muntwyler**).

<table>
<thead>
<tr>
<th>Year</th>
<th>Installed quantity</th>
<th>Total quantity of material (to)</th>
<th>Dominant technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2050**</td>
<td>12'000 MWp</td>
<td>480'000 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
<tr>
<td>2050**</td>
<td>24'000 MWp</td>
<td>960'000 tons</td>
<td>Poly-+ mono-Si (&gt;80% market)</td>
</tr>
</tbody>
</table>

Tables 1 and 2 illustrate that the material flows of PV systems in Switzerland today are still relatively small and in the range of several hundred tons per year. Still they increase by a factor of around 1,000 by 2050. The figures suggest that it is worth planning and building up the future recycling for the expected material flows in advance. As explained in section 1.3, current recycling in Switzerland is quite simple and is based on the shredding of c-Si PV modules in hammer mills and further processing of material particles in Germany. The amount of PV modules recycled in Switzerland in 2017 (see section 1.2) corresponds to an output of less than 3 MWp. This quantity will rise to 50,000 tons per year in the coming years (corresponding to 1GWp per year). For example, the oldest and largest PV plant in Europe (Fig. 4) on Mont Soleil (CH) is waiting for disposal (Fig. 4), i.e. an estimated 60 tons of PV module material, plus assembly structures, cables and inverters.
quired 1,250 kg of material for 50 kWp of power. The new multi-string inverter from ABB only 125 kg for 120 kWp. This is an improvement by a factor of 24 in material efficiency! The efficiency has been improved and prices massively reduced.

2.3 Recycling of PV storage systems
If additional decentralized PV storage systems are used, further considerable quantities of material are installed. In this case not only the battery modules, but also considerable electrotechnical components such as the housing, terminals, cables etc. must be considered. These are easy to recycle. Storage systems in Switzerland are subject to the state obligation (INOBAT) and are processed by the company Batrec in Wimmis (Canton of Berne). Here, Li batteries are recycled according to a hydro-metallurgical process (www.inobat.ch).

3 CLASSIFICATION OF THE QUANTITIES OF MATERIAL TO BE EXPECTED IN THE FUTURE

The total amount of 960,000 tons of PV modules installed in 2050 calculated for the variant with 24 TWh electricity yield in Table 2 seems high. But how high is it in a relative context? For the whole Swiss population this corresponds to 120 kg of material and an output of 3 kWp (approx. 20m² area) per capita. This means that electricity can be generated for a 30 years timespan.

Furthermore: The 20m² area per capita is equal to an increase of the recycled material by approx. 5 kg (incl. inverters, etc.) per capita or an increase of 50% of the recycled electrical scrap by SENS eRecycling compared to the year 2015. This means that recycling in the Energy Strategy 2050 does not represent an additional order of magnitude.

Compared the amount of recyclable PV material with the total weight of a car, the largest and most expensive product of an average adult living in Switzerland, the total weight of all cars in Switzerland is already 10 times higher (8 million tons) than all PV modules used in Switzerland in 2050 to generate 24 TWh of electricity per year.

The 30 years of electricity production mentioned above are equivalent to 3 generations of cars, i.e. 24 million tons of material. However, every car still needs spare parts, lubricants and almost one ton of petrol per year, i.e. 4.5 million tons of fuel per year or 135 million tons of fuel in 30 years. These 135 million tons of petrol for Swiss cars in 30 years can be replaced by PV electricity, resulting in a recyclable PV module quantity of 960,000 tons. The future belongs to such leverage effects. It goes without saying that this is also more economical. After all, a PV module is much simpler than a car (see Chapter 1) and therefore easier to dismantle and recycle.

Nevertheless, there is still potential in the construction of PV systems to separate PV modules for the recycling process in an even better and faster way and with greater purity. The PV industry can learn a lot from the automotive industry, which has been practicing this for some time. For example, most PV modules today are designed with an aluminum frame. In the future we could see a trend towards glass-glass constructions. This would possibly increase the weight, but the aluminum frame would be omitted. This would improve the energy balance of the PV modules and possibly increase their service life. An increased service life would improve both the economic efficiency of the solar power and the material balance. Completely new designs are also conceivable, possibly based on thin-film technologies, a development that is now more than 20 years old (Solarex Millenia solar modules, flexible Uni-Solar triple modules, etc.). Lightweight modules are another trend.

4 THE MATERIAL OF A PV SYSTEM HAS SEVERAL LIVES (SECOND LIFE)

The material of a PV system has several "lives". It is worth taking this into account when planning PV systems.

4.1 Plan for dismantling and repowering of PV systems

There is a growing interest in the energy balances today is whether new or recycled modules are installed in 2050 calculated for the variant with 24 TWh electricity yield in Table 2 seems high. But how high is it in a relative context? For the whole Swiss population this corresponds to 120 kg of material and an output of 3 kWp (approx. 20m² area) per capita. This means that electricity can be generated for a 30 years timespan.

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4.2 Provisions for the dismantling of plant and equipment

When it comes to financing the deconstruction, the plant operators are in demand and must make provisions for the deconstruction of the plant. This can be done through reserves, e.g. from the "Arbeitsgemeinschaft für dezentrale Energieversorgung ADEV" in Burgdorf. Another strategy is to amortize the plant in 25 years which is the usual period today. The deconstruction could be financed with the extra yield after the regular lifetime of 25 years ("planning by hope..."). It is not very recommendable to pass these costs on to the next plant operator.

4.3 No critical components and materials for CH-PV standard modules

No critical materials are to be expected for the crystalline silicon PV modules predominantly used in Switzerland. This is different for thin-film technologies, which are rarely used in Switzerland for facades and buildings. Copper could be a critical component here. It is already an expensive material today and will certainly become more expensive in the future. Instead of copper, the light metal "aluminium" is available. It is indeed more difficult to use and needs a slightly larger cross-section with a slightly lower weight. At the end the entire electrical industry will face this challenge.

4.4 Energy balances massively positive

Insiders have known for decades that the energy balances of PV modules are very positive, without recycling even in the range of a factor of 30 but have not yet been discussed everywhere. Recycling can further improve energy balances. For example, the main part of calculating energy balances today is whether new or recycled aluminum is used for the frame.

5 PROSPECTS

Still little agreement and much uncertainty or ignorance is found in the published literature regarding the materials, energy and material flows used in connection
with PV modules. The SENS eRecycling Foundation and the PV Laboratory of the Bern University of Applied Sciences (BFH) have therefore established a cooperation to address the existing uncertainties and create the necessary transparency. Joint research efforts are being undertaken on lifetime, material transparency and recycling for both PV systems and PV storage systems. The challenges are easy to solve, because the materials are well known and can already be easily recycled today. The quantities to be expected in the future are large, but in familiar proportions. There is still much potential in the business models for the design, assembly and dismantling of modules, the recycling of materials and objective information on the energy and material flows of recycled PV systems.

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References:

i Energiestrategie 2050; Urs Muntwyler, www.pvtest.ch, 2017
ii Langzeitmessung von PV Anlagen; Urs Muntwyler, PV Labor BFH-TI, www.pvtest.ch, 2018
iii Praxis mit Solarzellen, Urs Muntwyler, 1986, 75 ff; Franzis Verlag München
iv Muntwyler SolarHandbuch, Urs Muntwyler; 1991, S. 3ff; Muntwyler Energiotechnik AG
v Persönliche Information, SENS eRecycling, Frühling 2018
vi Urs Muntwyler, PV Tagung Staffelstein, 2016
vii Persönliche Information, SENS eRecycling, Frühling 2018
viii Persönliche Information, SENS eRecycling, Frühling 2018
ix Checkliste zum Erstellen einer Energiebilanz, 2014, Unterrichtsmaterialien Wahlmodul „Nachhaltigkeit für Ingenieure; BFH-TI, 2014, PD Dr. Eva Schüpbach
x www.pvtest.ch, diverse Beiträge
xi Swissolar, PV Markt Schweiz, 2000-2015
xii Untersuchung MSE Studenten/ Urs Muntwyler, Sommer 2018 (unveröffentlicht)
ixiii Tabelle „Wechselrichter“, Urs Muntwyler; MSE-Kurs „Photovoltaik“ 2018
ixiv Tabelle „Wechselrichter“, Urs Muntwyler; MSE-Kurs „Photovoltaik“ 2018
ixv Tabelle „Wechselrichter“, Urs Muntwyler; MSE-Kurs „Photovoltaik“ 2018
ixvi Checkliste zum Erstellen einer Energiebilanz,