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Scalability Of CPV Towards Multi-Gigawatt Deployment

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Abstract. In this work we assess to which extent the manufacturing of CPV components and systems is scalable towards deployment on the level of several GW of annual new installations. The problem of scalability is analyzed on two levels: A. short-term scalability, as a function of the industry's capability for scaling up its annual manufacturing capacity, and B. long-term scalability, as a function of availability of materials resources and reserves. Both levels are investigated throughout the industry's value-chain: from Germanium wafers towards installed CPV systems.

Keywords: CPV, scalability, manufacturing, capacity, materials resources, availability, germanium.
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INTRODUCTION

CPV is a relatively new solar technology, and as such has recently started to be manufactured and deployed on an industrial, respectively commercial scale. CPV deployment can grow sustainably into the multi-GW scale, only if the whole supply chain of the industry can support that growth both on the near-term in terms of capacity build-up, and on the long term in terms of materials resources and availability. In this paper we will explore the capability of the CPV industry on both levels, throughout the whole value chain, from Germanium wafers, over multi-junction cells, towards system assembly. We will focus on CPV-specific materials and production processes, not on more generic support industries and standard electro-mechnical systems such as trackers and inverters, for which there is ample capacity and there are no potential materials availability constraints.

GERMANIUM SUBSTRATES

Most of the high-efficiency multi-junction cells which are used at present for the production of CPV systems, are based on germanium wafers. The germanium wafer in a cell has a double functionality: it constitutes the bottom cell, and it serves as substrate for the epitaxial growth of the III-V layers which form the higher bandgap middle and top cells.

Germanium is widely dispersed in the earth's crust, and has been estimated at an average concentration of 6,7 parts per million (ppm) [1]. There are no real germanium minerals , but only minerals who contain important amounts of germanium [2]. Hence the abundance of germanium is orders of magnitude lower then of silicon, and therefore the question may arise whether there are sufficient germanium resources to enable a sustainable and substantial growth of CPV for large scale power generation .

Build-Up Of Production Capacity

The currently installed global germanium wafer production capacity is estimated at 1.5 million wafers/year (4 inch equivalent), distributed over multiple suppliers, while new entrants are expected as the CPV market will grow. Of those 1.5 million wafers, between 100,000 and 200,000 were used for CPV cell production in 2011.

At today's optical concentrations and system efficiencies, 1 MW (AC) of installed CPV power consumes on average 1500 Ge wafers (4 inch equivalent). Thus, the currently installed global wafer capacity corresponds to 1GW of CPV power. As one Ge wafer (4 inch equivalent) represents less than 10g of Ge material, 1 GW of installed CPV power requires less than 15 metric tons of germanium.

From table 1, the annually accessible Ge resources amount to 255 metric tons. The current total annual demand for non-CPV applications is between 100 and 130 metric tons, leaving an additional 125 to 155 tons yearly available for CPV application. This corresponds to an annual installation of more than 10 GW of CPV power, at today's concentration and efficiency levels.

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The industrial flowsheet of Ge for CPV involves refining, crystal growth and wafer processing, including recycling of process wastes throughout the flowsheet. Typical ramp-up rates of production capacity in the industry today are at a level of some 100,000's wafers/year, corresponding to a ramp-up rate of some 100's of MW of CPV system production capacity per year. A ramp-up speed increase of the Ge wafer industry by a factor of 10 is technically feasible, which means that the Ge industry's future capability for scaling up is several GW/year of ramp-up rate. This potential ramp-up rate is further increased by the projected decrease of the required number of wafers per MW installed CPV power, through the increase of cell and system efficiency (see par. 2) (Figure 1).

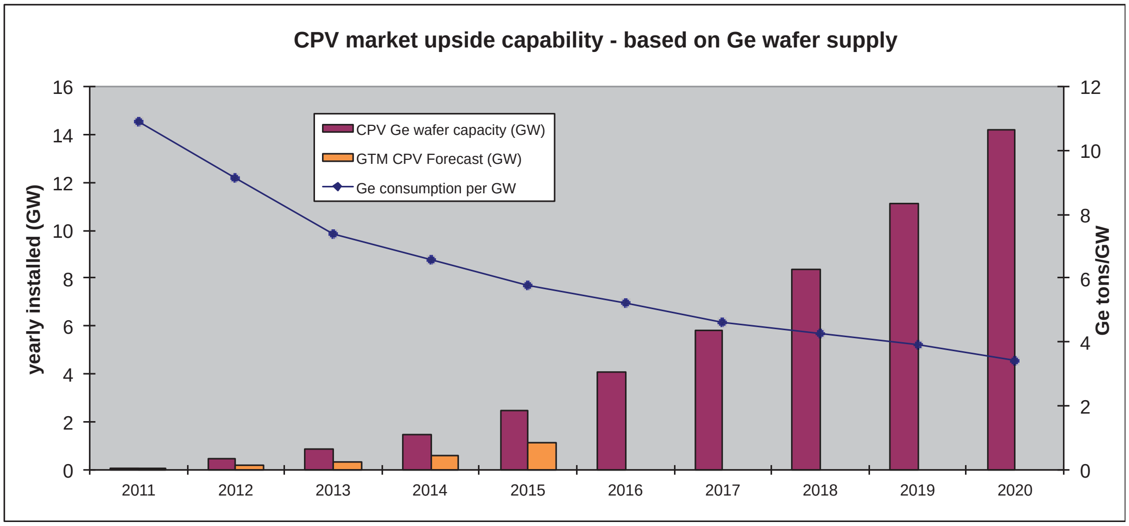

FIGURE 1. CPV market upside capability based on the potential capability of the Ge industry for ramp-up of Ge wafer production capacity. The lower bars which run through 2015 represent the 2011 forecast by GTM Research for the growth of the CPV industry

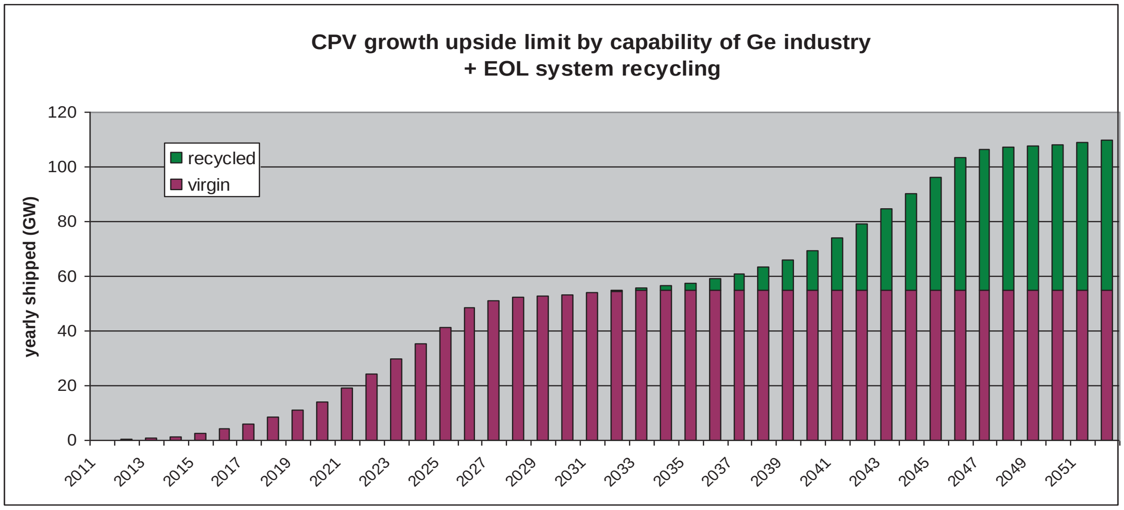

FIGURE 1. Long term CPV market growth upside potential enabled by the availability of germanium and the projected decrease of Ge consumption per installed MW of CPV power. The green bars starting from 2033 represent add-on installment capability through recycling of Ge from the end-of-life systems which were installed from 2011 onwards.

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Long Term Material Availability

TABLE 1. Availability of Germanium.

(in metric tons)	Annually accessible	Global reserves
	255	> 15000

The global reserves of germanium amount to more than 15000 metric tons. At today's levels of concentration and efficiency, full utilization of these reserves for CPV would enable a cumulative installment of CPV power upto the TW level.

Taking into account a yearly availability of 125 metric tons for the production of CPV cells (see par. 1.A)[1], and a gradual decrease of the required amount of Ge per GW through the increase of efficiency and manufacturing yield (from 11 mt/GW in 2011 down to below 3 mt/GW in 2030), the Ge availability would allow for an annual installation of above 50 GW of CPV power by 2030. If we moreover assume a full recyclability of the Ge from end-of-life CPV systems, we come to the graph depicted in figure 2.

This implies that the germanium availability can support the CVP industry growth forecast with significant upside capability.

MULTI-JUNCTION III-V CELLS

For the analysis of potential bottlenecks in the production of CPV solar cells, the source materials availability and cell production capacity are to be taken into account.

High efficiency solar cells for CPV applications are based on III/V semiconductor structure consisting a stack of p-n junctions (currently, 3 junctions are state-of-the-art) and separated by tunnel diodes. In terms of chemical element usage, Gallium (Ga) is considered as the most important component as it is required for both, GaAs middle and top InGaP sub-cells.

Although Ga is a rare element that appears almost exclusively as a trace component in some minerals like bauxite and zinc ores, the known reserves of bauxite and zinc ores allow winning more than 1 million tonnes of metallic Ga [3], which will cover any long-term industrial needs. In the CPV solar cell production via MOCVD technology, Ga is used in form of metal-organic compound trimethylgallium (TMGa) also required for production of a range of optoelectronic devices like LEDs. The estimation of TMGa demand for solar cells with an efficiency of 40 %, like e.g. AZUR 3C40 cell type, and operating at 500x sun concentration results in 1 kg of TMGa/1MW(AC) CPV plant. Compared to the worldwide production volume of TMGa, which has consisted in 2011 of about 40-45 tonnes mainly supplied to LED industry, even 1GW of new CPV installations expected in 2015 (s. GTM Research forecast figure) presents a minor value.

In the next future, backlighting and general lighting LED markets are expected to remain the key consumers of TMGa. Accordingly, production capacities of major suppliers of metalorganicsAkzo Nobel, Dow Chemical and EpiChem were recently extended and also followed by setting up few new manufacturers in Asia. These capacities are certainly available for CPV industry too and override solar cell material related limitation for CPV up-scaling.

Since the development of first GaAs-based multi-junction solar cells, metal-organic chemical vapour deposition (MOCVD) technology is the most established way for producing CPV solar cell structures as it allows excellent material quality and homogeneity and, at the same time, very rapid process times. This is still not possible by competing deposition technologies. For the state-of-the-art cell structures, manufacturing of 1 GW of CPV modules per year (for the operation at 500x suns) is well covered by approx. 30 MOCVD reactors. This is less than the total machinery park already installed at CPV cell manufacturers.

The continuous trends in the CPV manufacturing are the transition in the wafer size from 4” to 6”, increase of the cell efficiency and, last not least, development of CPV modules with higher light concentrations. The combination of these factors shall lead to the decrease of the amount of solar cell wafer required per MW as it is shown in Fig. 3. In 2020, 5 to 7 MOCVD reactors only shall be able to cover 1GW CPV installation demand.

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[1] The Ge consumption for non-CPV applications is expected to remain stable at current levels at least up to 2020

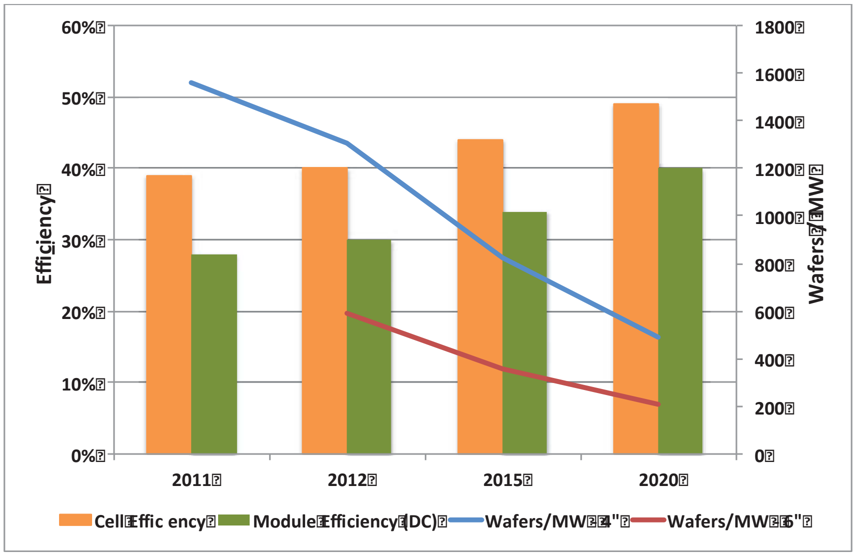

FIGURE 3. Roadmap for CPV solar cell/module efficiency and solar cell wafer demand per MW.

NON-CELL COMPONENTS AND SYSTEM INTEGRATION

A consideration of CPV systems indicates that these have substantial ability to scale, both in the long term, and in the short term, as long as judicious decisions impacting the cost of manufacturing, installation and maintenance are implemented at the design stage.

Long Term Scalability: Material Availability Of Non-Cell Components

CPV System: Use of Widely Available Materials

Table 2 lists the primary components of typical CPV systems along with the base materials that are incorporated in the components. The main materials used are steel, aluminium, glass, acrylic and/or silicone (for optical components), electronic components, adhesives, concrete, wiring and other Balance of Plant equipment.

These materials are widely available and commonly used in other high volume industries such as the construction and automobile industries. Because of the non industry-specific nature of the materials, there is no anticipated shortage of supplies on any of these items. That is one of the key features of CPV which makes it a highly scalable technology.

TABLE 2. Main Materials in CPV Power Plants.

Component	Description	Materials
Receiver	Contains cell and circuit board connecting the electrical output of the CPV cell to the wiring of the CPV panel. Also includes cell thermal management and may include optical components.	Circuit board, cell, wire
Optical System	Two primary types: reflective Cassegrain type optics (ex: SolFocus) and refractive Fresnel lens type approaches (ex: Soitec).	Glass, acrylic, silicone, silver, aluminium
Panel Enclosure	Mechanical and environmental enclosure protecting and supporting the power units.	Glass, aluminium, acrylic
Tracking System	Structure to support the CPV panels and provide motion.	Steel, concrete
Electronic Control System	Electronic boards for telemetry, control, data-acquisition, positioning algorithm and actuator control.	Classic electronics
Field Installation	Components common to most PV systems: wiring, fencing, inverters and transformers, metal or concrete foundations	Wire, concrete, inverters and transformers

The majority of the materials used in CPV systems can be locally sourced, making distributed global manufacturing very feasible. This is in contrast to all Si solutions, where large, centralized plants are needed. The main centralization needed for CPV is the cell, which is not a huge areal component of the module. Centralized plant for optics may or may not be necessary depending on the process, but they are more robust components than Silicon wafers, so transport will be easier if a centralized plant is used for that component.

Examples of the material split by weight of current commercial CPV systems are shown in figure 4.

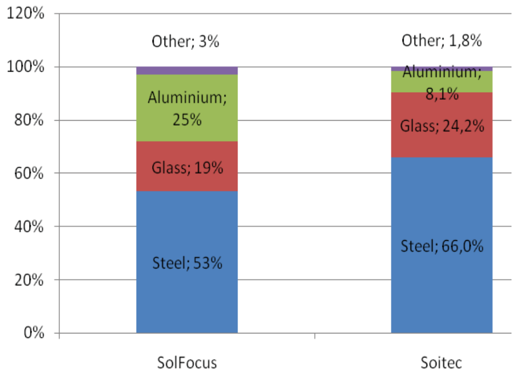

FIGURE 4. Main materials used in current commercial CPV Systems.

Efficiency and Recyclability

Additional features inherent to CPV solutions further enhance the ability of these technologies to optimize their use of materials and be amenable to long term high volume scaling. These features include (1) a steep efficiency increase over the next decade requiring fewer systems to generate a given amount of power, and (2) a very high recyclable content allowing reuse of many of the materials next decade requiring fewer systems to generate a given amount of power, and (2) a very high recyclable content allowing reuse of many of the materials.

Efficiency:

The high efficiency of HCPV panels, reaching around 30% today, will continue to increase substantially over the next 10 years, leveraging both design optimization, but also the very significant efficiency growth of the multi-junction cells. This will continue to drive less material usage across the entire system compared to non-concentrating PV (Figure 5).

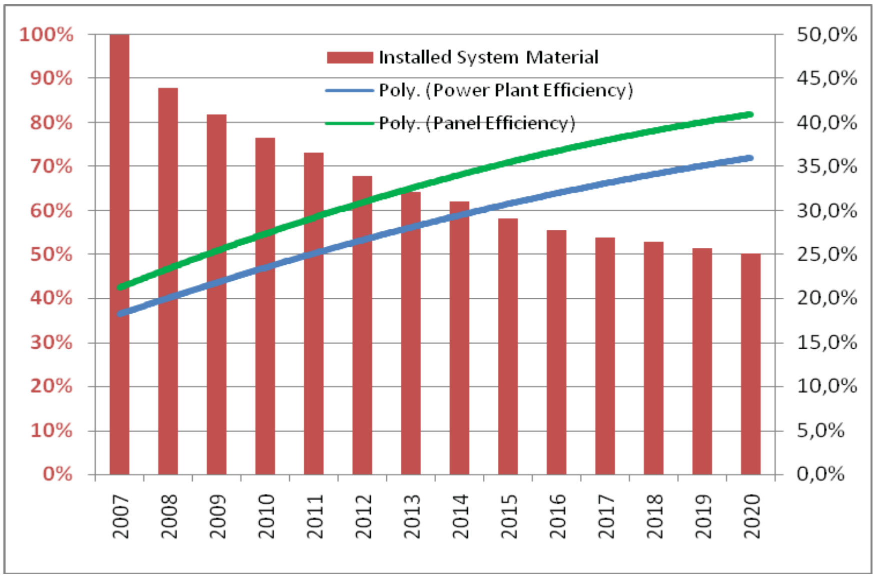

FIGURE 5. Efficiency trajectory and impact on material usage over time. This is an aggregate for a number of CPV systems surveyed in October 2011 [4]. Actual efficiencies for leading CPV companies may be higher.

Recyclability:

The vast majority of the material content of CPV systems is highly recyclable, with a typical recyclable content exceeding 95%, and one of the lowest energy footprints in the industry. See Figure 4 for the material composition of leading CPV systems.

Given the generic nature of the materials making up CPV power plants, the reducing material requirements and the high level of recyclability, the long-term ability of CPV manufacturing to scale to accommodate growth in CPV demand will not be considered further here.

TABLE 3. Recycled Content and Recyclability of Materials used for CPV Systems.

Material	**Recycled Content**	**Recyclability**	**Applications**
Steel	65-100% according to which manufacturing process is used	100%	Complete reuse of scrap material for steel production
Concrete	25-45% according to application	100%	Surcharge for primary concrete production Padding of line trenches Base and anti-freeze layer in road construction Foundation ground improvement
Glass	Due to high purity requirements, recovered glass is not used for float glass production	100%	Float glass shards are used for the production of container glass if purity requirements are met
Aluminum	Up to 100%	100%	See steel

Near Term Scalability

For near term scalability, CPV manufacturers need to be able to quickly ramp up their manufacturing base and deploy large sites efficiently and economically. In the absence of material constraints, an important consideration is the cost required to do so. Design decisions can drive significantly different cost structures in terms of manufacturing, but also installation and maintenance. Achieving low costs at scale, and hence high scalability is dependent on having product design criteria that target not only high performance, but also consider the all inclusive cost of manufacturing, logistics, installation and maintenance.

Manufacturing:

The capital expense of manufacturing is an important factor in determining which technologies are well suited to high volumes. Some of the factors that need to be considered from a manufacturing perspective, as well as examples of challenges that can drive up these costs, are listed in table 4.

CPV is inherently an assembly operation. Being able to leverage on existing high volume methods means that, despite CPV being a new technology, once the design is mature, its manufacturing ramp is facilitated by known, proven high volume techniques and not newly invented processes or capital equipment.

By careful implementation of criteria such as those shown above as part of the initial design process, commercial CPV companies have been able to optimize capital expenditure and minimize factory ramp up times.

Capital expense of the order of \$0.12-0.30/W with footprints of 25000 sqft/100MW (~2320m^2/100 MW) have been achieved, with a factory ramp up time of 6 months from green field site to fully operational facility.

TABLE 4. Important investment cost factors for high volume manufacturing of CPV systems

Manufacturing Cost Factors	**Impacts**	**Scalability Enablers**
How large is the factory footprint required for a certain throughput?	Cost of Factory	Fast assembly with limited number of steps, for example: High acceptance angle simplifying alignment process and allowing high tolerance budget Quick cure adhesives Short re-work loop Very high yield Suitability for cost-effective automated manufacturing
How standard or customized is the manufacturing equipment?	Cost of Equipment	Moderate size enabling use of commonly available automation. High acceptance angle simplifying alignment process and allowing high tolerance budget
How time-consuming are the assembly and testing processes?	Time to Manufacture, Cost of Equipment	High Acceptance Angle simplifying alignment process and allowing high tolerance budget Moderate size, simplifying manipulation Short re-work loop
How many parts need to be sourced and assembled?	Cost and complexity of supply chain	Small BOM, enabled for example by passive cooling and venting. Use of widely available materials and components.
How many systems fail quality check and need to be re-worked?	Time to manufacture	High Acceptance Angle simplifying alignment process and allowing high tolerance budget

Deployment and Maintenance:

Similarly, the product design needs to take into account the impacts on logistics, installation and maintenance costs to allow scaling to high volumes. Some of the characteristics that can be considered to support this are listed in table 5.

Consideration of criteria such as these has enabled commercial CPV companies to dramatically optimize shipping costs, and installation and maintenance activities, supporting high volume deployability.

TABLE 5. Deployment and maintenance aspects which support scaling

Cost Area	Considerations	Desired Characteristics
Logistics	Simple logistics	Moderate size, fits in standard shipping enclosures (pallets, containers).
High speed installation	Minimize on-site assembly activities, simplify unloading and packaging.	Pre-assembly, limited leveling requirements (high acceptance angle), well-designed packaging and dispatching.
Limited Maintenance Requirements	Cleaning Tracker Maintenance Trouble Shooting	Easy to clean systems (ex: tough front glass). Low maintenance motors and gears, requiring very infrequent maintenance. Well designed control system enabling availability of performance information and alerts.

CONCLUSIONS

This assessment shows that a scale-up of the CPV industry to a level of several GW of annual new installations is not restricted by materials availabilities and reserves. The near term challenge is the capability of ramping up manufacturing quickly. This is mitigated by the suitability of the technology to efficient assembly-type manufacturing, resulting in low manufacturing capex, footprint and ramp-up time.

As a general conclusion, the CPV industry’s supply has the capabilities to support the forecasted CPV market growth with significant upside capability.

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