How facilities can affect energy consumption in PV cell production

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ABSTRACT
The production toolset is not the only significant source of power consumption in PV cell production. Cooling water, climatization, pressurized air and, in some cases, clean-room conditions drive up the electrical energy demand. In addition, the geographical location influences the cooling energy demand for air handling, resulting in a non-negligible contribution to electrical power consumption. The extent of this additional consumption over and above the toolset demand depends on whether the structure of the facility systems is 'traditional' or 'smart'. This is demonstrated by a number of quantitative examples in this paper.

Introduction

This paper examines which portion of the power consumption required for the fabrication of a PV cell is due to facilities, and in particular the options that exist for reducing this consumption. The facilities present a number of significant 'power consumers', because of the requirements of the production toolset: energy supplies of different types (electrical, thermal, pressurized air), gases and chemicals, and services for the disposal of exhaust and waste water or used chemicals. As some cell manufacturing is carried out in clean-room environments, this will also lead to a power consumption related to clean-room operation. All the facility services require power, mostly electrical, for their function.

The parameters of last year's example modelization [1], which was performed mainly to show the interdependencies of water and energy consumption, have been refined in the light of recent total energy consumption data [2]. The aim of this investigation is to enable a ranking of the contributions to be made, and to determine which of these are worth looking at and offer promising optimization potential. Two questions are tackled: 1) to what extent is the range of results determined by assumptions on facility structure?; and 2) what is the relationship of the facility contribution to the electrical power demand of the process equipment toolset? These questions will be restricted to crystalline PV cell production (mono/multicrystalline) and to the choices of facility configuration that actually occur in practice.

Facility structure for PV cell fabrication

The fraction of electrical power consumed by facility applications is shown in Fig. 1, which is based on the compiled data in de Wild-Scholten [2] and an estimated breakdown in de Wild-Scholten & Schottler [1]. The absolute numbers are distinctly lower than those given in the ecoinvent 2.2 database and in Schmidt et al. [3]; however, they are based on recent data collection and are expected to reflect the overall advances in PV cell fabrication. It can be seen that a significant part of electrical power consumption is attributable to the production facility, and, as it turns out, substantial variations in this consumption can be induced by varying the design of the facilities.

> "A significant part of electrical power consumption is attributable to the production facility."

In general, thermal and electrical energy are provided from sources external to the site. Thermal power usually has three major destinations: office heating, climatization purposes and exhaust treatment. Whether heating is also necessary in wastewater treatment, ultrapure water generation or other facility locations depends on the details, and so this aspect is not taken into account in the following analysis. Heating for the process equipment, on the other hand, is usually performed electrically. Electrical power is more widespread in its use than thermal power, which means that a variety of end uses have to be considered, and not just a small number as in the case of thermal power.

The main facility consumers of electrical power which will be considered are cooling power production, air handling, bulk gas production and compressed dry air production. These relationships are shown in an overview in Fig. 2, and are independent of the nature (mono/multicrystalline) of the fabricated PV cell. Several scenarios are investigated in the following analysis, which lead to improvements, some with lower power consumptions but others with increased consumptions. The reason for this is to highlight potential influences and their relative importance.

Bulk gas generation, mainly nitrogen in PV fabs, is not shown in Fig. 2; it is also not varied in a dedicated scenario, although its contribution is not negligible. Nitrogen is produced either onsite or offsite. In the latter case it is transported to the site in liquid form and stored there in tanks. In most projects these particular installations are contracted to a company other than the

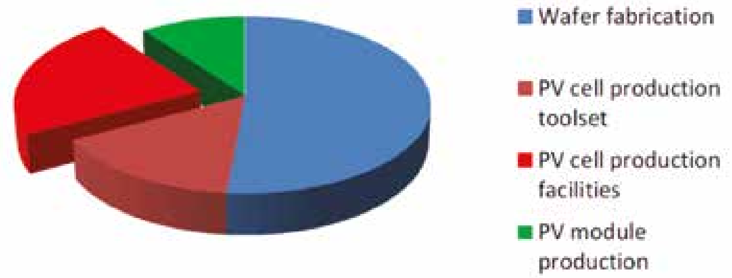

Figure 1. Contributions to the electrical power demand for the fabrication of a c-Si PV module.

fab designer, and energy consumptions are kept strictly separate and confidential, because a manufacturer's production cost is critically dependent on the specific energy consumption during nitrogen production. This energy consumption has been evaluated at 0.75kWh/kg N_2 with the dataset in Schmidt et al. [3], and has been included in the result charts for comparison purposes, but does not undergo any variation.

Facility services, such as ultrapure water generation or treatment of general and corrosive exhaust air streams, that are considered to be minor in terms of electrical power consumption have not been highlighted in detail, in order to keep the breakdown lean. The same is true for office heating and cooling and waste water treatment.

Scenarios investigated

All the scenarios are based on a production throughput of 9,600 wafers (156mm × 156mm) per hour.

- **Scenarios 1 and 2:** Standard scenarios based on available databases and reports. Scenario 1 shows ecoinvent 2.2 data for the sake of comparison; however, they appear outdated and excessively high. Scenario 2 is considered the standard scenario in the following, and is based on the compilation in de Wild-Scholten [2]; it corresponds to the facility structure in Fig. 2. Several design criteria are varied relative to this standard scenario, and the overall results inspected.

- **Scenario 3:** Includes cogeneration.

- **Scenario 4:** Includes cogeneration and an absorption chiller (see Fig. 3).

- **Scenario 5:** As for the standard, but with an additional loop for processing cooling water at a higher temperature than in the coldest loop.

- **Scenario 6:** As for the standard, but uses an ISO class 5 (formerly class 100) clean room.

- **Scenario 7:** As for the standard, but with cold dry winter/hot summer conditions (see Figs. 4 and 5).

- **Scenario 8:** As for the standard, but with constant hot humid outside conditions (see Figs. 4 and 5). A comparison of scenarios 7 and 8 will show how much the influence of climate on the energy required for air handling affects the results.

- **Scenario 9:** As for the standard, but with a biofilter instead of an RTO (regenerative thermal oxidizer) for VOC (volatile organic compound) exhaust treatment.

- **Scenario 10:** Includes all positive options, as well as the geographical location.

Cogeneration (scenario 3) means the production of electrical power is onsite, which is usually chosen because of the superior stability of the power generated with respect to small or large interruptions. However, it is also beneficial in terms of energy efficiency:

- Transportation losses of electrical power are avoided.

- Power generation is based on natural gas, which has a smaller CO_2 footprint in highly efficient devices than, for example, coal or the power mix in most countries.

- Waste heat from power production can be used for heating purposes, replacing other fuels with natural gas.

The values for assessing CO_2 equivalent emissions are: 1) 500g CO_2/kWh.el, which is close to the EU power mix with approximately 30% coal in the power mix [4]; and 2) 150g CO_2/kWh.th for natural gas – a conservative value, including quite substantial escaping methane emissions during gas production [5].

In addition to the advantages of scenario 3, scenario 4 includes the generation of chilled water using the waste heat of power production, thus eliminating the need for electrical power for the generation of cooling power. This is performed by absorption chillers.

The corresponding schematic block diagram for scenario 4 is shown in Fig. 3. Only natural gas is taken from the environment, with all the rest taking place within the production site.

Scenario 5 is again based on the standard facility structure, but provides three cooling loops instead of two. The coldest loop (usually 6°C, but sometimes less) feeds just the fresh air treatment (and some other, minor, applications), whereas all the other functions – such as return air, process equipment and office climatization – are driven by chillers, yielding 12°C cooling water. In small installations, this loop is often fed by heat exchangers connected to the 6°C system, but separate generation has efficiency advantages, as well as being cost-wise feasible if a certain minimum size of installation is exceeded.

To assess the energy savings possible with three cooling loops instead of two, the coefficient of performance (COP) value of the mechanical chillers needs to be estimated. The COP represents the cooling power in kW (th) that can be generated by 1kWh of electrical power consumed by the compressor of the chiller. It depends on many factors, including the point of operation and the actual supply and return temperatures achieved under certain operating conditions. If the system is not operating at full cooling power, for example, or has been overdesigned in terms of

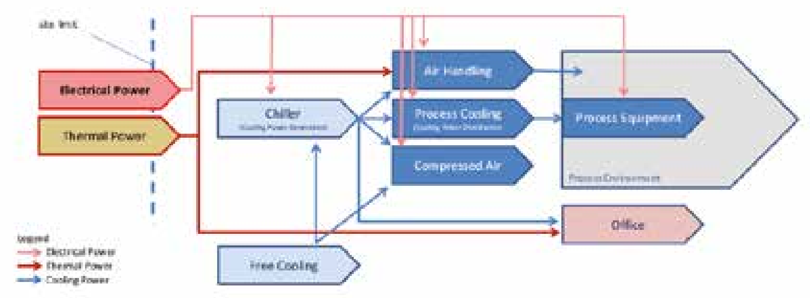

Figure 2. Standard structure of facilities for PV cell production.

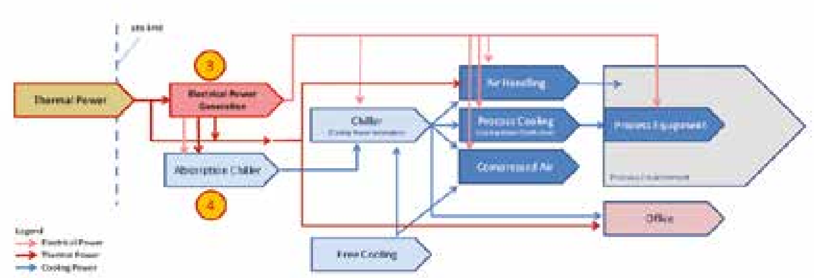

Figure 3. Cogeneration and absorption chiller (scenarios 3 and 4 respectively).

volumetric cooling liquid flow, the supply and return temperature spread decreases, negatively affecting the COP and thus decreasing energy efficiency. Chiller manufacturer data therefore have to be interpreted with care. For the present study, the COP values and their differences for the different chiller types have been set to conservative values in order not to overestimate the energy savings. More details are given in de Wild-Scholten & Schottler [1].

Air handling can in general be divided into fresh air, return air and exhaust air treatment; these are considered in scenarios 6 to 9. Return air is addressed in scenario 6, and fresh air in scenarios 7 and 8. Exhaust air treatment is addressed in scenario 9, but only in part of the VOC treatment, because other types of exhaust are unimportant energy-wise.

Scenario 6 investigates how clean-room conditions for production have an impact on the energy demand and balance. Generally, clean-room conditions affect the power demand of return air management: not only can the demand per m^2 of installed clean-room space be higher than per m^2 of the normal production area, but also the pressure drop of the return air is higher than with normal return air.

It is clear that the settings of non-clean-room return air conditions require some assumptions on the structure and conditions of operation of the air-handling system. The calculations in the scenarios, other than scenario 6, assume some air recirculation, but at lower pressure drops and lower air flow rates than in scenario 6. Certainly more savings in air handling are possible, but this should be the subject of detail engineering in a specific project. Here, it was preferred to produce cautious comparisons without overemphasizing the differences.

The outside air conditions have a major influence on fresh air treatment. This treatment phase consists of process stages for controlling temperature and humidity, and bringing the temperature and humidity of any outside air to within a specification-compliant range by heating/cooling and humidification/dehumidification. A usual process sequence (without filtration stages) is:

- Preheating
- Ventilation
- Humidification
- Dehumidification (by cooling, typically down to 8°C)
- Reheating (typically up to 22°C)

If the outside air is hot (as in scenario 8), the cooling power required for dehumidification purposes is significant, as is the reheating power to reach 22°C in the production environment. More important than this use of power, however, is usually the cooling power required for removing water from the outside air if humidity is high, as in the case of scenario 8.

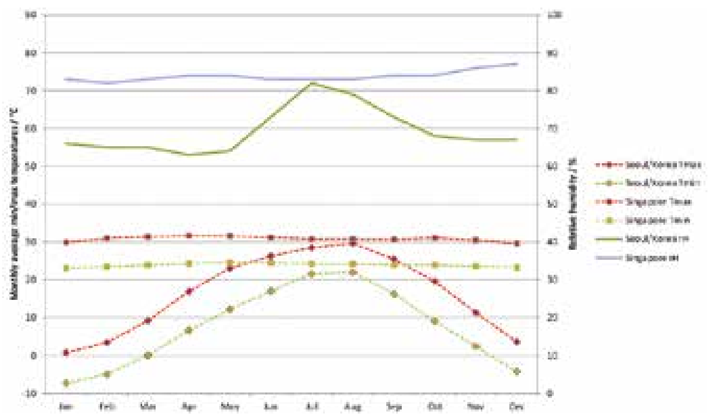

Figure 4. Climatic conditions (monthly averages) for Seoul/Korea and Singapore in 2015.

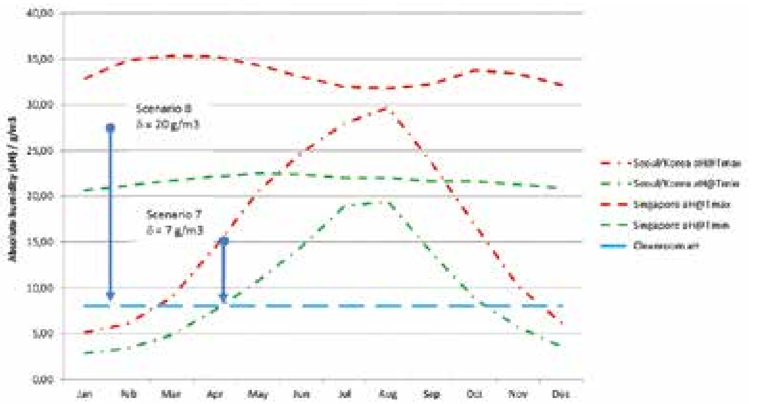

Figure 5. Absolute humidities of the fresh air at the entry to treatment.

Climatic outside conditions and their impacts on the energy demand are compared using scenarios 7 and 8. Two sample locations were chosen for the comparison: Singapore and Korea. Climate data for 2015 were acquired from the internet [6] and are presented in Figs. 4 and 5. The relative humidity data given were converted to absolute humidities (which are necessary for the calculations) by using the respective minimum/maximum temperatures from the monthly averages and the vapour pressure curve, as taken from ProSim Plus software. For the sample calculations presented here, it was assumed that a yearly average cooling is required from 28 to 8°C in scenario 8, and from 12 to 8°C in scenario 7 (see temperature data in Fig. 4). The absolute humidity, on the other hand, was assumed to have decreased by 20g/m^3 air in scenario 8, and by 7g/m^3 in scenario 7 (see humidity data in Fig. 5).

Although the nearly constant climatic conditions of scenario 8 allow an easy visual check of temperature and humidity differences, in scenario 7 there is a day/night cycle that needs to be taken into account before assessing the net difference in temperature and humidity. Moreover, in scenario 7 there is no need for dehumidification during three months of the year, but instead humidification is required, as can be seen from Fig. 5. For every month during which the absolute humidity of the outside air is lower than the clean-room air specification, humidification is necessary rather than dehumidification. In the months where the absolute humidity of the outside air is lower than the clean-room air specification for the minimum (night-time) temperatures, humidification is also necessary for certain hours during night time. All this makes it impossible to verify straightforwardly the reported 7g/m^3 reduction setting; however, it might be taken as a given and typical value. For a specific project, an analogous evaluation can be run very precisely using climatic data that are available around the world, though not all free of charge. This is the recommended approach for specific projects, because significant differences can even occur in the same country, and more details of the air-handling system have to be addressed than are reported here.

Scenario 9 considers a special case of exhaust air treatment: whereas exhaust air treatment in general has not much impact on overall energy consumption, the so-called RTO installation for VOC treatment consumes much more thermal power than a biofilter solution. This effect is more pronounced in the VOC exhaust in PV cell fabrication than in other types of production, because a preconcentration cannot take place, as explained in Hottenroth & Schottler [7]. A preconcentrator is an adsorption system, most often based on a turning adsorber wheel; this subjects the VOC to adsorption and desorption, resulting in an air flow with a lower rate than the original one, thus leading to an increase in concentration of the VOC in the air to be treated. Terpineol, one component of VOC exhaust in PV cell fabrication, would polymerize on the adsorbent media used for preconcentration and thus ruin it in a short time.

The absence of a preconcentrator forces the RTO to operate under suboptimal operating conditions, although these systems usually exhibit a heat recovery rate of 93%. Biofilters are environmentally favourable systems, but require strict technical control of their function in order to obtain satisfactory operational behaviour. Only a strict and efficient growth control of the bacteria in the filter can prevent unpleasant and sudden pressure build-up or unexpected system downtime.

Detailed environmental impact studies, including the power consumption aspect, have already been reported in the literature [8–10], and so scenario 9 is included for the sake of comparison.

Scenario 10 is the best case, combining the most favourable conditions. Since most of the effects found are additive, the savings relative to the standard scenario were added up. Because the favourable cases were cautiously estimated, scenario 10 is considered to be a realistic best case, and not a hypothetical one.

> "Chilled water generation can be clearly identified as the most important contributor to the facility power consumption."

Results

Two main charts were produced in order to highlight the results. First, the electrical power demand of the facility section is given in total and also broken down into major contributors; all are compared with the electrical power demand of the process equipment toolset (Fig. 6). Here, the chilled water generation can be clearly identified as the most important contributor to the facility power consumption, followed by air handling (in total, i.e. all contributions counted together, except VOC treatment). The bulk gas generation, which was not varied or inspected in detail, is next in importance, and the compressed dry air (CDA) generation after that. The 'rest' category encompasses other applications such as office cooling, ultrapure water generation, waste water treatment or simply lighting. This category is calculated from the overall power consumption given by de Wild-Scholten [2] and the sum of the other indicated facility structures; it undoubtedly also exhibits some error or uncertainty. However, it is apparent that most of the major contributions could be identified and ranked.

What the chart in Fig. 6 does not show are thermal power consumptions. The total site CO_2 equivalent emissions were calculated taking into account both thermal and electrical power consumptions (Fig. 7). Here, the VOC treatment, which mainly requires additional thermal power in the case of an RTO, is included in the calculated balance.

It is striking how high the emissions are for the outdated consumption data in scenario 1, and how much scenario 10, the best-of-all combination, is lower than today's standard value in scenario 2. Clearly visible is the bad influence of hot humid weather (scenario 8), as well as the superior performance of a cogeneration combined with an absorption chiller (scenario 4). The latter is usually combined with several dedicated cooling loops (scenario 5). If an ISO class 5 clean room is necessary (scenario 6), additional power is required compared with scenario 2.

The weather influence (scenarios 7 and 8) has already been discussed in detail and is mainly due to differences in fresh air treatment.

Scenario 9 on the whole consumes less thermal power compared with the standard scenario; this is the benefit of biofiltration.

When the results of Fig. 7 are taken in combination with the production rate of PV cells, the difference relative to the average footprint of the final cell can be expressed in grams of CO_2/kWh.el for the best and worst cases:

- Best case (scenario 10): –3g CO_2/kWh.el
- Worst case (scenario 6/8): +1.5g CO_2/kWh.el

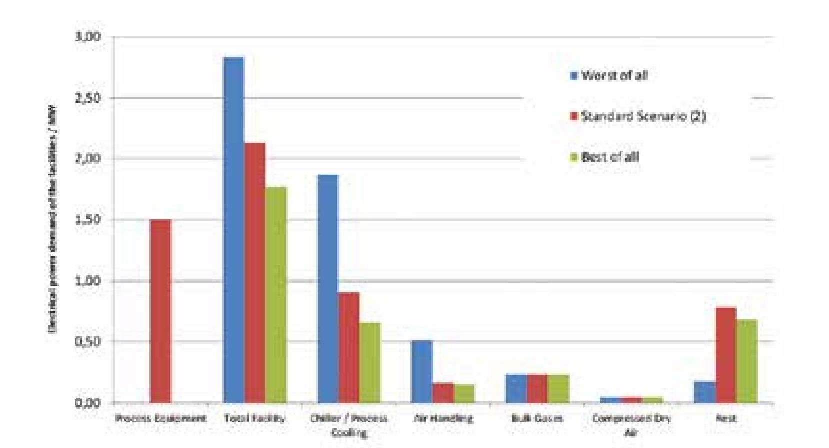

Figure 6. Electrical power consumption per facility installation and scenario.

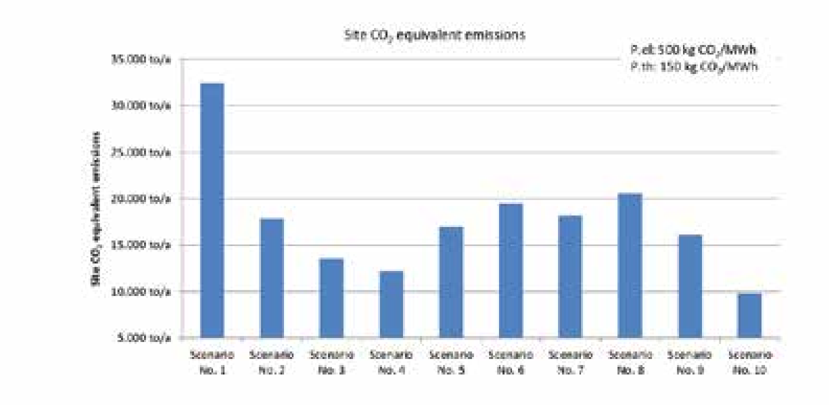

Figure 7. Site CO_2 emissions resulting from the different scenarios.

It is interesting that the 'good' side has more potential than the 'bad' side, at least in the light of the set of scenarios chosen and presented here. When old process and facility designs are used, even higher consumptions/emissions are possible, as can be seen from the older data [2,3]; these data are not incorrect, but rather relate to another generation of production technology.

Discussion

A general design criterion which improves the CO_2 footprint is the installation of cogeneration with the use of waste heat by absorption chillers. This avoids the direct usage of electrical energy from the network and thus leads to savings in CO_2 equivalent emissions, whenever there is a power mix with significant fossil fuel contribution in the country of consideration. Irrespective of this decision, the cooling power required is one of the major contributions to the facility power demand. Cooling power is required by production tools, but also by air handling; the latter largely depends on the geographical location (local climate) of the production facility. Hot and humid locations drive up the air handling cooling demand.

Exhaust air handling does not usually have a significant impact on energy consumption, except in the case of VOC treatment. The standard VOC treatment systems installed in many PV fabs have considerable natural gas consumptions, and a new design should preferably take into account biofiltration methods. The next most important contribution is nitrogen gas, mainly used for process purposes (flushing) and vacuum pump purging. Any reduction in consumption that is achieved here helps to reduce the overall energy demand. Of lesser importance is CDA production, and of even lesser importance are other facility services (ultrapure water generation, wastewater treatment, lighting, office equipment/heating, etc.) which were excluded from the detailed breakdown shown here.

The best situation is achieved with the production in a country that has cold dry winters and dry summers, installation-wise consisting of a cogeneration with absorption chillers and a minimum of three different cooling loops of chilled water, and a VOC exhaust treatment using biofiltration. This arrangement is highlighted in scenario 10.

Of course, many more variations are possible in the facility engineering of PV cell production; some of the major cases should be analysed in order to determine what part facility design plays in the significant bandwidth of power consumption. With the particular integrated energy flow model cited [1], every variation can be calculated and assessed. This, however, is usually done within the framework of a specific project. For example, there are ways of overcoming the negative influence of a humid geographical location, but these installations have to be integrated into the design from the very beginning of the project.

Conclusions

In respect of the large variation between the best and worst scenarios, two conclusions can be drawn. First, a detailed engineering procedure that takes into account the power-saving potentials is mandatory. Second, a PV cell manufacturer should certify its production with regard to specific energy consumption, to turn the engineering efforts made during facility design into a competitive advantage.

> "A PV cell manufacturer should certify its production with regard to specific energy consumption."

An energy payback time attributed to a specific type of cell/module without referring to the manufacturer's facility structure or the climate of country of location may provide an indicative figure, but it is not precise enough to support buying and installation decisions from an environmental point of view. The CO_2 footprint of a solar cell produced under the best and the worst conditions can vary by as much as 4.5g CO_2/kWh, depending on facility structure and geographical location.

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