MODULARIZATION OF PRINTED CIRCUIT BOARDS THROUGH EMBEDDING TECHNOLOGY AND THE INFLUENCE OF HIGHLY INTEGRATED MODULES ON THE PRODUCT CARBON FOOTPRINT OF ELECTRONIC SYSTEMS

Tobias Kupka [a], Gernot Schulz [a], Thomas Krivec [a], Wolfgang Wimmer [b]

[a] AT&S AG, Fabrikgasse 13, 8700 Leoben, Austria
[b] TU Vienna, Institute for Engineering Design and Logistics Engineering, Austria

Abstract: Greenhouse gas (GHG) emission knowledge of company own production processes will be a necessary future asset, independently of the respective industry. To meet future environmental goals, the knowledge of greenhouse gas emissions related to products is critical. This can be assessed using a product carbon footprint (PCF) approach, assessing the greenhouse gas emissions of a product over its product life cycle. The production of electronic systems, which include active or passive components as well as printed circuit boards (PCB), is characterized by the use of emission intensive materials such as precious metals, polymeric dielectrics or organic process chemicals. Available data show that the product carbon footprint of those electronic systems is mainly determined by the amount and type of materials used to build up the system. Increasing the degree of integration of an electronic system, by means such as embedding of active or passive dies into the PCB build-up, allows achieving a significant reduction of the size of the system or module. Thus, the integration of separate functions into an integrated module is considered as one promising way to improve the PCF of electronic systems. The presented study deals with the comparison of an electronic system based on surface mount technology with a highly integrated functional module, which is produced applying embedding technologies. Process flows were investigated in detail and documented. Assessment was done following ISO 14067 - "Carbon Footprint of Products" in which the inventory (energy, materials, waste, transportation) was gathered and the impact was calculated using emission factors from Ecoinvent 3.4 database. Results of the study show a large impact of type and amount of used materials as well as a significant potential to improve the PCF by size reduction of the system, which favors embedding technology over the traditional manufacturing approach.

1. INTRODUCTION

The electronics market is rapidly growing, due to the increased use of mobile devices and eventually many of our items of daily use will be *smart* and *connected* constantly. One of the main components of an electronic device is its printed circuit board (PCB), mechanically holding all electronic components and electrically connecting them to ensure the function of the product. Production of PCBs is highly energy intensive and metals like copper and gold are very critical base materials to ensure conductivity.

As the share of electronics is growing in more and more products like cars, household appliances or industrial machines, more and more PCBs are produced all over the world. In addition, mobile devices like smartwatches, smartphones and tablets are standard accessories worldwide, with a decreasing life span.

In parallel, the effects of man-made climate change can already be seen, as weather extremes occur more frequently and both average temperatures and sea levels are rising. [1] The global community is therefore required to look for possible ways to reduce greenhouse gas emissions on the planet. Manufacturers of electronic products are increasingly under pressure, due to their high production volumes and environmental impacts.

To reduce the carbon footprint of electronics industry, new ways to save materials are sought. With the embedding of electronic components inside of PCBs, one possible future approach to save emissions is presented in this work – a technology that may contribute to future achievement of emission goals in electronics industry.

2. ECP TECHNOLOGY

With embedded component packaging technology (ECP), electronic components (active or passive) are embedded into the printed circuit board during production. These integrated components are then connected to the surface of the board by copper plated micro vias (small laser drilled holes which are electrically conductive).

The ECP technology has various advantages. A maximum of 45% of the inner area can be assembled with components, which otherwise would have been mounted on the surface, resulting in free space and therefore enabling further miniaturization of PCBs and subsequently of electronic modules. Other advantages are the protection of sensible components, reliable interconnections, improved thermal management, performance gains and higher data rates through proximity of components inside the board. [2], [3]

3. METHODS, GOAL & SCOPE

The environmental performance of two printed circuit board production technologies (standard multilayer and ECP technology) at the production site in Leoben was assessed by conducting a product carbon footprint (PCF) assessment, following the ISO 14067 -- Carbon Footprint of Products.

The ISO 14067 standard describes the term Product Carbon Footprint (PCF) as the "sum of emitted and extracted greenhouse gases over the life cycle of a specific product." Its value is stated representative for all greenhouse gases in a reference value of kilogram carbon dioxide equivalents (kg CO_2-eq). [4]

The carbon dioxide equivalent (CO_2-eq) is a unit enabling a comparison of the radiative forcing of a greenhouse gas to the radiative forcing of CO_2. The CO_2-eq is calculated by multiplying the mass of a given greenhouse gas emission by its 100 year global warming potential (GWP 100a). The carbon footprint considers all four greenhouse gases and two groups of gases, defined by the Kyoto Protocol. [4], [5]

To draw general conclusions of the two technologies in focus, the PCF of two specific reference products, which are manufactured using the observed technologies, was assessed. First, all material and energy flows of production processes were gathered. With these data available, the PCF of the products was calculated using emission factors gathered from Ecoinvent 3.4 database.

The results of the assessment were then used to draw general conclusions of and compare the environmental performance of standard and ECP production technology. Following the ISO 14067, basic conditions are clarified in the following section.

For the PCF calculation, two specific PCB products, currently produced at AT&S Leoben, were chosen. The first product was a common rigid 6-layered product, with a size of 431,4 mm x 25 mm. The second product was a rigid 4-layered PCB with an embedded component inside (ECP technology) and a size of 4,55 mm x 4,35 mm. These two specific products will further also be referred to as *reference products*.

3.1. Functional unit

As consumption data of production processes could only be gathered per the internal production format of AT&S and not per single PCB this size is declared as the functional unit (FU) for the PCF calculation. One functional unit equals one production format of PCBs. For the standard product this is measuring 21"x 24" (532,4 mm x 609,6 mm), for the ECP product 18"x 24" (457,2 mm x 609,6 mm). The functional unit covers all production processes including the milling of the production format into single PCBs as well as the final packaging of the PCBs. In case of the standard product, it is milled into 15 PCBs, so one functional unit consists of 15 final PCBs. At the ECP product, one panel is milled into 1456 PCBs, one functional unit therefore consists of 1456 final PCBs. The embedded electronic components of the ECP product are not included in this functional unit.

Because of the large differences concerning the actual product function of the PCBs, the results of the two calculated PCFs were not comparable regarding product function without further adjustment, which will be addressed in Section 6.

3.2. System boundaries

As a manufacturer of PCBs, AT&S is providing service to business customers (B2B). Therefore, the boundaries of the evaluated system were set to a cradle-to-gate approach regarding data up to the finished product, before leaving the company. It includes the life cycle stages of use of raw materials and manufacturing and is assessing all GHG emissions up to the the point where a product is leaving the "gate" of the company, before being sent to customers. This makes sense if products are not directly sold to end-consumers from the production facility, like PCBs. [5]

This approach is including all upstream processes, meaning all energy and material used for resource extraction and the manufacturing of supplied materials. The stages of distribution, product use and end-of-life were not included in this assessment.

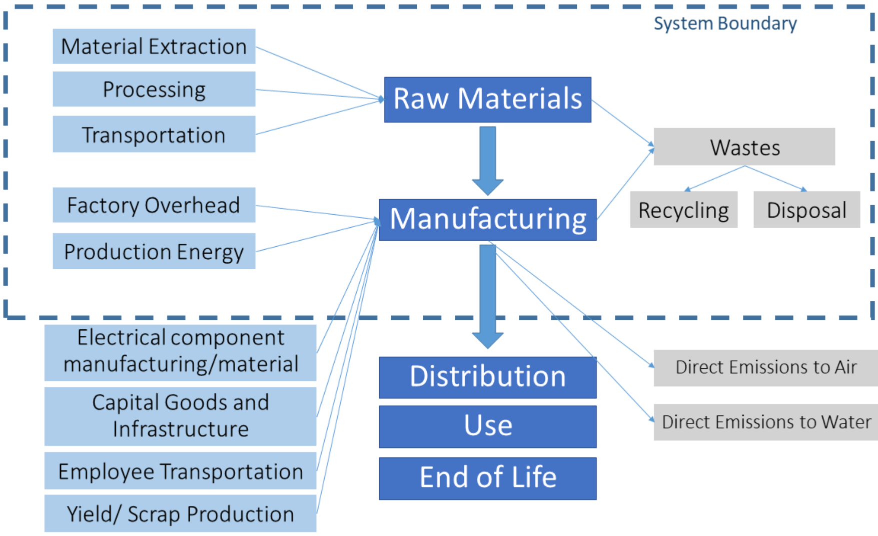

Figure 1: System Boundaries

The applied system boundaries of the assessment can be seen on Figure 1. On input side, all emissions related to material extraction and processing are included in the assessment, including upstream processes. Also, transportation of materials to the manufacturing plant in Leoben is included. At the manufacturing level, emissions due to energy consumption of production machines and due to energy consumption and material use of overhead processes are included into this assessment. The factory overhead is defined as processes not directly related to the manufacturing of the product such as air conditioning or heating of the facilities.

On the output side, the waste resulting from the manufacturing and material production is included, also the recycling processes for the used materials and waste are included as well as the transportation to the recycling facilities.

Not included in the study are the manufacturing of the components embedded into the ECP product are the materials used for it, since the functional unit was defined as the PCB without electrical components. Also, capital goods and infrastructure of the company are not included in the calculation. Further, employee transportation (to and from workplace, business trips) is not included in the study, as this is described in the product category rules (PCR). Due to missing data, also the impact of scrap products, meaning PCBs which are produced but disposed before packaging are not included in this assessment.

At the output side, direct emissions to air and water are not included in the system boundary, as these are considered negligible due to installed air washers and the wastewater treatment. This consideration was made in accordance with the responsible department for plant exhaust gas at the company.

3.3. Cut-off criteria

Waste items under 0,1% of the total waste generated at the whole production plant in the year 2016 are excluded from the study. Data were gathered from the waste department of the company for the entire production volume of 2016. No further cut-off criteria is used in this study.

3.4. Geographical scope

The PCBs were manufactured in Leoben, Hinterberg between September 2017 and January 2018. Materials were sourced worldwide.

3.5. Allocation

Due to the differences of available consumption data and installed meters as well as the given possibility to measure directly on site during production, following allocation methods were applied in the study.

3.5.1. Allocation of production data

The reference products were followed through the whole production procedure, to be able to gather primary data directly on site during production. Where it was possible, electric energy consumption data was measured directly at the production machines during manufacturing of the product. Where this approach was not possible, own company records of data (SAP data) was used instead.

Due to unavailable data regarding the panel-sizes of products passing through the machines when using SAP data, process consumption data (electric energy, water, chemicals) were allocated generally to one panel, regardless of the smaller or larger panel size. All main material data (mass of core, prepreg, copper) was allocated to the actual production panel size, therefore this assumption is considered to have a minor impact on the results.

If possible, electric energy consumption data were directly measured on site during production of the reference PCBs using a portable electric energy meter (Type Hioki 3169-20). The collected data were then divided by the number of panels passing through the machine during the measurement. This approach was mainly used for electricity measurements. If this was not possible, the following allocation approach was used.

When consumption data could not be acquired by direct measurement, but through installed water, electricity or chemical meters at the machine, total monthly consumption data of electric energy, water or materials were gathered. Throughput data (panels passing through this machine in the considered time frame) were then gathered from own company data records (SAP system). The required data per panel were then calculated by dividing the gathered consumption data by the amount of panels passing through the machine. If a meter was not available at a specific machine, but only covering areas of more than one production line, throughput data for the whole area were gathered. This approach was used for most water and chemical consumption data.

3.5.2. Overhead allocation

To allocate the energy and material consumption of the overhead processes to one single functional unit, an estimation of 50000 monthly produced panels in the whole production facility, regardless of the specific products was used. No actual data were available for the monthly panel output of the whole production facility, therefore this is an approximation based on the number of panels passing through the solder mask process over one month. As basically every panel is passing through this process step only once and this data were available, this is considered an applicable estimation.

Monthly consumption data of overhead processes were gathered through the installed meters and divided by 50000. For processes with fluctuations on energy consumption over the year, such as heating and air conditioning, average monthly consumption data were used for the allocation.

3.5.3. Waste allocation

As an estimation for the produced panels in the specific year, the same estimation was used as described before, resulting in 600000 assumed panels a year. Waste data were mostly allocated the same way as described for the overhead processes. The disposing data of the year 2016 provided by the company were the primary data source.

For the two largest waste values "copper chloride" and "copper containing sludge", special calculations were made to provide a more accurate estimation:

Copper chloride is accumulating at the etching lines. Therefore, the total number of panels undergoing an etching procedure over a year was determined from the SAP system. The total amount of copper chloride waste in the year 2016 was then divided by the gathered number of panels, resulting in an approximate amount of copper chloride waste per etching process. Because an average product is undergoing the etching process three times, the calculated consumption value was multiplied by three, resulting in an approximation of 2,7 kg of copper chloride waste per produced panel.

The amount of copper containing sludge waste per panel was determined similarly. This disposing item is accumulating at the copper plating processes. Therefore, the total number of panels undergoing a copper plating process over a year was determined. The total amount of sludge disposed in the year 2016 was then divided by the gathered number of panels, resulting in an approximate amount of copper containing sludge waste per plating process. Because an average product is undergoing two copper procedures (horizontal copper and final copper plating), the calculated consumption value was multiplied by two.

3.6. Temporal context

All electric energy consumption data, measured on site were gathered between September 2017 and January 2018. If monthly data were gathered from installed meters and the SAP system, data of September 2017 were used. If monthly average data were needed, the average over the year 2017 was used. For waste disposing values, only data for the year 2016 were available, so these were included in the assessment.

3.7. Data types and data quality

In this section, all data sources used for the assessment of the PCF will be described. Also, information regarding uncertainty in the provided data will be stated. Used data is classified in primary data and secondary data. Primary data is defined as data based on direct measurement on site or on calculations which are based on direct measurements on site. Secondary data is defined as data based on other sources than direct measurement on site. An overview of the data quality can be found in Table 1. [4]

Table 1: Data Quality

Data	Data Quality	Comment
Primary Data		
Amount of materials used in production	Excellent	Few missing data due to inoperative meters, below 1%
Amount of electricity used in production	Excellent	Gathered directly on site
Amount of electricity used in overhead	Excellent	Gathered directly on site
Distance of supplier transportation	Satisfactory	About 53% of supplier data
Amount of waste generated	Satisfactory	Old data from 2016
Distance to recycling facility	Good	About 95% of data available
Secondary Data		
Emission factors of materials	Good	Some missing; Some from chemical supplier, not verified; About 10% of data missing.
Emission factors of transportation	Excellent	
Emission factors of electricity	Excellent	
Emission factors of recycling	Poor	About 40% of data available

3.7.1 Primary data

To collect primary data during this assessment, a specific customer order of the reference PCBs was followed through the whole production sequence over five months. Starting from the main materials up to the packaging of the final product. Data were either gathered directly at the machine while products were manufactured using a portable electricity meter or monthly data were read from installed meters electric energy, water or chemical meters. The measuring instrument used was a *HIOKI 3169-20 CLAMP ON HiTESTER* with three *HIOKI 9660 CLAMP ON SENSORS* for the three phase lines. Through this method data of the required materials and required electric energy during production and overhead processes was gathered.

Due to inoperative or missing water and chemical meters, some consumption data could not be gathered. Most missing data concern water consumption, which do not directly affect the PCF. The missing consumption data for chemicals are estimated to be well below 1% of the total volume of chemical consumption, based on observations on site and information from the machine operators.

Transportation distance of material acquired was gathered from suppliers directly. Through contacting each supplier, about 53% of all distances and forms of transportation, regarding the transport of supplied material to the production plant could be gathered. For the transportation routes of the waste to the recycling facilities about 95% of the distances could be determined through the disposal companies.

3.7.2. Secondary data

Basically all secondary data, namely emission factors for the global warming potential, were gathered using the Ecoinvent database 3.4 using the cumulative life cycle impact assessment (LCIA) with IPCC 2013 method. The global warming potential over 100 years (GWP 100a) was used to gather the emission factors with the system model: "Allocation at the point of substitution". At Ecoinvent version 2 this allocation method was the default method, therefore this was used. [6]

In cases where the origin of materials sourced by suppliers could not be defined , the global dataset (GLO) was used. Data regarding the electric energy emission factor were gathered accordingly to the available energy mix. The natural gas emission factor for Austria was applied.

Some additional emission factors were received from a major process chemistry supplier. These values were used but could not be verified, because no information concerning the actual chemical composition of these chemicals was provided by the supplier.

For about 10% of all specified materials, no emission factors could be provided, either because datasets were not available or the actual ingredients of special chemicals could not be identified. However, with regard to one functional unit, the mass of these materials with missing emission factors is well below 1% of the total used materials mass, these materials were neglected in the further calculations..

Furthermore, for some chemicals the emission factors gathered in Ecoinvent were adapted to the specific chemical concentration. If for some factors, the exact material was not available in the database, a closely related dataset was selected.

Recycling processes carried out by disposal companies external to AT&S are very complex and hard to track. There for the most part, it was not possible to gather much data on waste processing outside of the company and it was even harder to find actual emission factors of disposal and recycling processes. The impact of recycling on the PCF therefore needs to be considered as a rough estimation. All recycling related emission factors found were taken from Ecoinvent 3.4.

3.8. Uncertainty

Due to missing data as described, there is some uncertainty remaining in the assessment. Looking at primary data, the overall data quality is very good. Only data related to material and waste transportation, regarding the transported distances, are not complete. Due to a generally low impact of material transportation on the results of this assessment, this incompletion is considered as a small uncertainty.

Concerning secondary data, the largest uncertainty is resulting from missing recycling data. Since no detailed data for recycling related processes are available there is the possibility that emissions caused by the recycling of materials might deviate from the values suggested in this assessment.

Overall, emission factors from Ecoinvent are based on calculations and assumptions. Therefore some uncertainty is also associated to the emission factors used, as documented in the Ecoinvent database 3.4. [6]. Finally as described the secondary data received from a chemical supplier could not be verified and is therefore remaining an uncertainty. Nevertheless, the total consumption of these chemicals is very low, therefore these data are not considered to have a large impact on the final results.

4. LIFE CYCLE IMPACT ASSESSMENT - RESULTS

The identified consumption data was used to assess the Product Carbon Footprint of the two reference products. For that purpose, the collected quantitative data (kWh, kg, l, m³) was multiplied by the corresponding emission factors resulting in the PCF. Summing up those values results in the final product carbon footprint of standard and ECP reference products. This was done with regard to one functional unit of each of the two reference products and results are shown regarding the assessed life cycle stages.

$$\begin{aligned} PCF = & \sum \Big\{ [Material\ Consumption \times Material\ Emission\ Factor] \\ & + [Material\ Consumption \times Transportation\ Emission\ Factor] \Big\} \\ & + \sum [Electric\ Energy\ Required \times Emission\ Factor] \\ & - \sum \Big\{ [Recycled\ Material \times Material\ Emission\ Factor] \\ & - [Recycled\ Material \times Transportation\ Emission\ Factor] \Big\} \end{aligned}$$

The product carbon footprint regarding one panel, PCB and m² of the standard reference product can be found in Table 2. The impact of used materials and associated transport on the final PCF is given separately. The required electric energy is shown as well and is split into electric energy required by production machines and electric energy required by overhead processes. The emissions regarding recycling of materials are also shown separately. One panel of this product consists of 15 PCBs, the final results of this assessment are displayed per panel, PCB and m².

Table 2: PCF Results for the standard reference product

	Position			
	Materials (incl. transport)		22,68	kg CO_2-eq
+	Electric energy production machines	27,55 kWh	6,75	kg CO_2-eq
+	Electric energy overhead	31,70 kWh	7,77	kg CO_2-eq
-	Recycling of materials (incl. transport)		4,48	kg CO_2-eq
=	**PCF per panel (532,4 mm x 609,6 mm)**		**32,71**	**kg CO_2-eq**
	PCF per PCB (431,4 mm x 25 mm)		2,18	kg CO_2-eq
	PCF per m²		100,82	kg CO_2-eq

The product carbon footprint regarding one panel, PCB and m² of the ECP reference product can be found in Table 3. The impact of used materials and associated transport on the final PCF is given separately. The required electric energy is shown as well and is split into electric energy required by production machines and electric energy required by overhead processes. The emissions regarding recycling of materials are again shown separately. One panel of this product consists of 1456 PCBs, the final results of this assessment are displayed per panel, PCB and m².

Table 3: PCF Results for the ECP reference product

	Position			
	Materials (incl. transport)		25,47	kg CO_2-eq
+	Electric energy production machines	77,81 kWh	19,06	kg CO_2-eq
+	Electric energy overhead	31,70 kWh	7,77	kg CO_2-eq
-	Recycling of materials (incl. transport)		4,48	kg CO_2-eq
=	**PCF per panel (457,2 mm x 609,6 mm)**		**47,82**	**kg CO_2-eq**
	PCF per PCB (4,55 mm x 4,35 mm)		0,03	kg CO_2-eq
	PCF per m²		171,59	kg CO_2-eq

5. LIFE CYCLE INTERPRETATION - DISCUSSION

In the previous section, two specific reference products were in focus and their product carbon footprint was assessed. The two gathered PCF values were differing (Standard: 32,71 kg CO_2-eq/panel; ECP: 47,82 kg CO_2-eq/ panel). This is a result of various reasons. First of all, different technologies (standard multilayer vs. ECP) were applied for the reference products, resulting in different process histories and different bill of materials (BOM). Also, functions as well as the areas of use of the products were different, the multilayer product will be used in a medical appliance, while the ECP product is a prototype for an embedded transistor.

In order to compare these two technologies it was necessary to look at two boards with exactly the same functionality, design and build-up, one being produced using standard and the other one using ECP technology. In reality, no such product is available, as a PCB is only manufactured using either of the two concepts.

To be able to compare the PCF of these two products and draw general conclusions for GHG emissions for the two technologies, together with experts of the PCB manufacturer, an approach was made to virtually create two products with the same function -- using standard and ECP technology. These virtual products were based on the actual ECP reference product and have the same function, namely a small PCB with a transistor component. In Figure 2, the concepts of the two virtual products are shown. in the SMT variant the component is mounted on the top of the PCB (standard) and for the second variant it is embedded into the PCB (ECP).

To achieve needed comparability in the product models, the following approach was carried out. It was defined, how the two virtual products would be manufactured in detail. Already collected data of the two reference products were split in "process modules" and the virtual production sequences were put together using the "process modules". Therefore, consumption data was already available even without actually producing both virtual products.

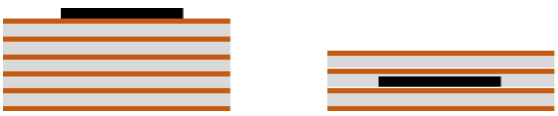

Figure 2: Build-up Concepts for the compared virtual products

5.1. Virtual product models

The following assumptions have been made concerning the development of two virtual product models. All of these assumptions are shown in Table 4.

As the previously assessed ECP reference product was considered a prototype, not the full surface area of the panel was utilized for production. 1456 PCBs were produced with one panel, only covering one sixth of the available surface area. To adjust the model to an actual mass production scale, this number was changed to full utilization of available surface area and therefore to 8736 produced PCBs with one panel.

Through the placement of components inside the printed circuit board, surface areas are freed up and the actual size of the board can therefore be reduced. Due to technical reasons, a maximum of about 45% of the inner area can be utilized for embedding of components, which concludes that the board can potentially reduce in size in about the same percentage. To ensure a realistic model of the virtual ECP product, an assumption was made that the surface area of the board will be reduced by 40% compared to a standard product with the same function. Also, it is assumed that the number of layers of the product can be reduced from six to four, due to easier connection of the component inside the board. Therefore, the virtual multilayer product is assumed to be 40% larger in size than the ECP product, resulting in 5242 PCBs on one panel.

Regarding panel size, both virtual products are defined to be produced in the smaller panel size, measuring 18 x 24 inches. This was carried out to enable the comparison of panels with the same size to each other.

Main materials such as core materials, prepregs and copper foil of the two reference products were not changed, as the used materials are significant for the used technology.

All production processes, which were not directly related to the used production technology (standard or ECP) were equalized as discussed below. This was carried out to ensure, that comparison would only focus on the used technology.

In detail, the number of drilled holes during "mechanical drilling" was equalized to 158160 holes. Also the number of times the processes "final copper plating" and "via filling" are carried out had to be adapted to ensure valid results. Further, the processes of "screen printing" and "flying-probe test" were removed from the virtual product models, as they were only included in the standard reference product. To equalize the models, these processes were not included in the virtual models since they are not related to the used production technology.

Due to the utilization of the full surface of the ECP panel, also some adjustments regarding ECP processes had to be made. The "laser drilling" and "laser cutting" processes were adjusted to the full utilization, resulting in an increased number of drilled and "cut" holes.

The assembly process is a process of mounting the components on or inside the board. To take the assembly process of the ECP product into

Table 4: All changes made to the product models to achieve comparable virtual products with the same functionality

	Standard	ECP	Virtual Standard	Virtual ECP
Panel size	large	small	small	small
PCBs per panel	15	1456	5242	8736
Mechanical drilling: drilled holes	15615	26360	158160	158160
Laser drilling: drilled holes	-	186924	-	1121544
Laser cutting: "cut" holes	-	274480	-	1646880
Final copper plating	1x	2x	2x	2x
Viafilling	-	3x	3x	3x
Screen printing	included	not included	not included	not included
Flying-probe test	included	not included	not included	not included
Assembly process	-	included	included	included
Gold amount per panel	0,22 g	1,42 g	1,42 g	1,42 g

account for the comparison, the material consumption and electric energy required by this process was added to the virtual product model of the standard product. The embedded component itself was not included in the assessment. [7]

The amount of gold applied to the surface of the reference products was significantly different. However, this is not directly related to the used production technology. Therefore, gold consumption on the surface of the virtual products was equalized, using the gold amount of the ECP reference product (1,42 g) for both virtual models to ensure comparability.

5.2. Results of virtual models

After establishing virtual products with the same function, only differing in the used production technology, a comparison regarding the PCF can be made. First, the results of the two products will be displayed, before going into more detail concerning their origin.

In Table 5 the final results of the PCF calculation for the virtual standard multilayer product are displayed. The impact of used materials and associated transport on the final PCF is given separately. The required electric energy is shown as well and is split into electric energy required by production machines and electric energy required by overhead processes. The emissions regarding recycling of materials are also shown separately in Table 5.

What can be seen is the higher PCF compared to the standard reference product. This is a result of the larger amount of gold applied on the surface as well as more electric energy required for the production of the virtual product due to the added copper plating processes. The PCF per PCB of the virtual standard product is much lower, because of the smaller product size.

Table 5: PCF Results of the virtual standard product

	Position			
	Materials (incl. transport)		41,58	kg CO_2-eq
+	Electric energy production machines	58,60 kWh	14,36	kg CO_2-eq
+	Electric energy overhead	31,70 kWh	7,77	kg CO_2-eq
-	Recycling of materials (incl. transport)		4,48	kg CO_2-eq
=	**PCF per panel (457,2 mm x 609,6 mm)**		**59,22**	**kg CO_2-eq**
	PCF per PCB (4,55 mm x 4,35 mm)		0,011	kg CO_2-eq
	PCF per m²		212,48	kg CO_2-eq

In Table 6 the final results of the PCF calculation for the virtual ECP product are displayed in the same manner as for the virtual standard product before. The additionally required electric energy for the production processes of the board is resulting from the full utilization of the panel size and therefore the increased amount of electric energy needed at the drilling processes.

Table 6: PCF Results of the virtual ECP product

	Position			
	Materials (incl. transport)		40,15	kg CO_2-eq
+	Electric energy production machines	99,90 kWh	24,48	kg CO_2-eq
+	Electric energy overhead	31,70 kWh	7,77	kg CO_2-eq
-	Recycling of materials (incl. transport)		4,48	kg CO_2-eq
=	**PCF per panel (457,2 mm x 609,6 mm)**		**67,91**	**kg CO_2-eq**
	PCF per PCB (4,55 mm x 4,35 mm)		0,008	kg CO_2-eq
	PCF per m²		243,67	kg CO_2-eq

The ultimate intention of the virtual products was to enable comparison of the two technologies, by one single PCB with the same function. As one PCB now provides the same functionality, regardless to the used production technology comparison is possible.

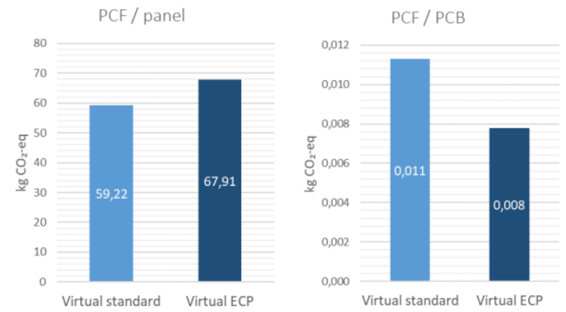

Figure 3: PCF of virtual products, per panel and per unit

When focused on one PCB, the ECP product is performing significantly better what can directly be seen as a result of the size reduction which the ECP technology allows. Considering only the panel, the virtual standard multilayer product shows a lower PCF compared to the virtual ECP product. However due to the fact that the standard panel consists of 5242 and the ECP panel of 8736 single PCBs, the result is changing in favour of ECP technology when compared by a single PCB as shown in Figure 3.

In Figure 4 the electric energy required by the production machines can be seen in comparison between the two technologies and two different points of view -- per panel and per PCB. Understandably, the electric energy consumption per panel is much higher regarding the virtual ECP product, due to additional processes carried out during production. If looking at the energy needed for production of one single PCB though, the result is again changing in favour of the ECP technology due to the size reduction of the PCB. These advantages regarding ECP technology are all caused by the miniaturization of the products, resulting in space for additional products on one panel.

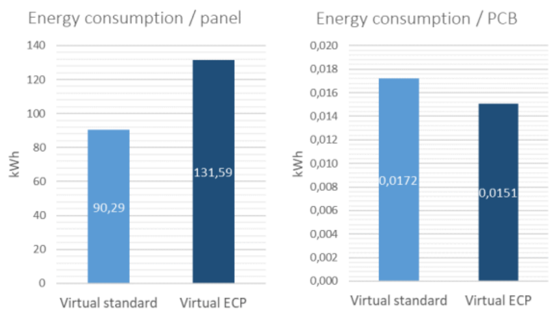

Figure 4: Electric energy required for production of virtual products per panel and per unit

The possible miniaturization and its effects will therefore be discussed in detail in the following section.

5.3. Influence of size reduction

All comparisons made so far were relying on the assumption of 40% size reduction due to ECP technology, which, based on available experiences, is to be considered as a realistic and achievable ratio. If this value can not be achieved due to various reasons, as for example the layout of the printed circuit board, the PCF advantage of the ECP board will decrease compared to the standard product. Figure 5 shows the impact of the achievable size reduction on the PCF of one single PCB.

What can clearly be seen is that starting with a size reduction of about 13%, the PCF of the ECP product is below the PCF of the standard product. This shows, that if the size of a PCB can be reduced by 13% due to ECP technology, an environmental advantage regarding the PCF can be achieved. At a 40% size reduction, the previously given results (Standard: 11 g CO_2-eq; ECP: 8 g CO_2-eq) can be found.

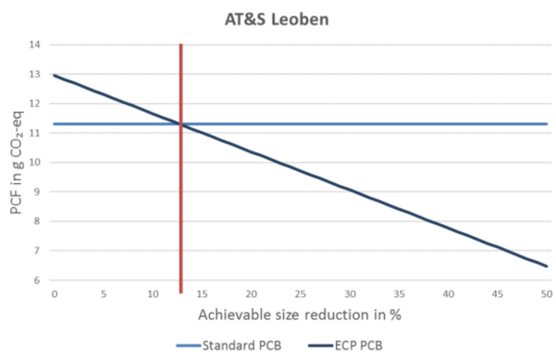

Figure 5: Influence of possible size reduction on the PCF

6. CONCLUSION

A comprehensive comparison of two PCB production technologies, standard multilayer and ECP technology has been carried out with regard to their PCF. The manufacturing process has been broken into single steps, the necessary data was acquired and a comparison has been done based on the ISO 14067 standard. As it has been shown, due to its potential to enable significant miniaturization the embedding technology opens the possibility to significantly reduce the environmental impact of electronic systems and modules,, characterized by a PCF reduction, when compared to standard multi-layer PCB technology.

7. REFERENCES

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