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Parametrized Manufacture Life Cycle Inventory of IGBT Power Module

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Keywords

Life Cycle Analysis (LCA), Power module, Modelling, Sustainable system, Parameter identification

Abstract

With escalating global environmental concerns and the need for sustainable technological solutions, it is necessary to assess the environmental impact of power electronics converters in the context of mass electrification of our societies. Life Cycle Assessment (LCA) is a mature method, but it relies on precise Life Cycle Inventories (LCI) to provide relevant estimations. However, given the challenges in obtaining manufacturing stage inventories from manufacturers, this paper aims to present a parametric LCI (PLCI) of power modules for the manufacturing stage based on experimental data inventory collected from several devices. The parameters considered here are based on the manufacturer's available geometric data in conjunction with material options and characteristics like the power module (PM) topology and number of dies. Both materials and processes are considered, and the model is made independent of the semiconductor technology, although one option is available. The method is presented here, and the inventory model is made fully available to support the LCA of power converters, including power modules.

Introduction

Power electronics is a key player in the decarbonation of our modern society, allowing us to maximize the efficiency of renewable energy power plants, connect them to the grid, and supply and drive most of our loads under high performance. Meanwhile, this considerable growth induces pressure on raw materials, and the manufacture of devices and products induces pollution. Most power electronics systems are wasted at the end of life (EOL) [1]. If decarbonation is necessary and must drive our energy transition from fossil to renewable energies, it must be done according to planetary boundaries and sustainable development. For this reason, implementing a Life Cycle Assessment (LCA) methodology is necessary to help analyze power electronics's environmental impact (EI). LCA is a method to assess EI based on databases, modeling methods, and tools that are well-mature today [2] [3]. However, the LCA remains dependent on the Life Cycle Inventory (LCI), which is the list of everything necessary (inputs or entrants) to produce, transport, use, and manage the end of life of the device under investigation and everything produced (outputs, extracts) for the same life stages.

Today, there is an important lack of data from power electronics manufacturers. This is a limiting factor for the accurate and valuable implementation of LCAs in the field.

To overcome this lack of data regarding the LCI of power modules, the idea proposed in this article is to develop a parametric Life Cycle Inventory (PLCI) of power modules based on data collected from the manufacturer and an experimental inventory of the materials composing the device, completed with a literature review regarding the associated processes and materials involved in the manufacturing stage. The parameters used for the model are basic and easily derived from manufacturer datasheets, enabling the creation of a complete

manufacturing LCI for a type of power module. This PLCI has been developed to be independent of the integrated semiconductor technology and adaptable to any semiconductor technology, such as wide band gap devices.

State of the art

Before 2018, most Life Cycle Assessment (LCA) studies on electric vehicles (EVs) focused on the entire vehicle system, often overlooking specific components like power converters. Notter et al. (2010) [4] explored the environmental impact of Li-ion batteries in EVs, emphasizing the challenges of obtaining detailed inventory data for electronic components, while Hawkins et al. (2013) [5] conducted a comparative LCA of conventional and electric vehicles but lacked important information regarding materials and production processes for powertrain electronics. While these studies provided valuable insights into the environmental impacts of EVs, they fell short of addressing the detailed inventory needs for components like power inverters.

This gap was later discussed by Nordelöf et al. (2019) [6] [7], whose work aimed to fill in these disparities by providing transparent and detailed inventory data for EV power inverters. Their approach emphasized the importance of accounting for variations in component weight, material composition, and performance parameters, offering a more accurate foundation for LCA modeling. The methodology is founded upon a parametric model that employs electrical specifications for the converter as an input and its mass composition as an output. It also incorporates a comprehensive inventory of inputs and outputs throughout the production phase, from gate to gate, aligned with the Ecoinvent 3 database.

To determine the parameters influencing mass approximation for the power module and its components, we analyzed the Nordelöf et al. (2019) dataset, revealing that rated power is the sole parameter for mass estimation, as shown by the equation:

$$\text{Mass}_{\text{module}} = \sum (\text{Mass}_{\text{substance @ 20 kW}} + \text{Scale factor}_{\text{substance}} \times (\text{Power}_{\text{User input}} - 20)) \quad (1)$$

The issue with this approach is that for different power ratings and power losses densities, for instance, the power modules can have disparate

masses due to the influence of component performances and/or design choices. Furthermore, the arrival of advanced semiconductor technologies, particularly the emergence of SiC and GaN components, which are more compact and offer enhanced efficiency, may render a mass estimate that solely considers nominal power an insufficiently precise representation. In light of these considerations, we have focused on developing a new parametrization method for the power module, with the methodology shown in the figure hereafter.

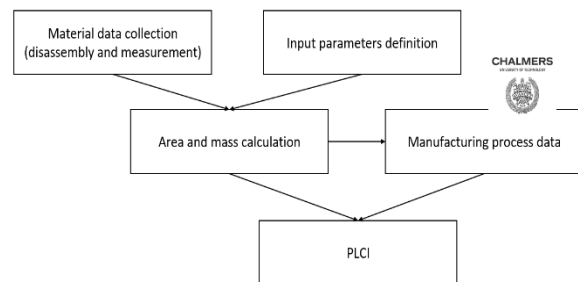


Fig. 1: Flowchart of the PLCI development.

Power module description and key parameters.

1 – Power module description

A power module, the heart of a power converter, is a device whose primary function is high-frequency switching of electrical quantities (I and V). Figure 2 below presents a cross-section of a regular power module, and Figure 3 presents a picture of a power module. It consists of several parts that must be identified from the perspective of LCI, as outlined below:

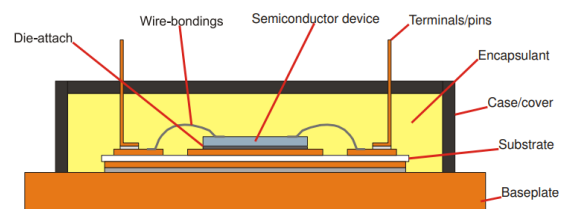


Fig. 2. Cross section of a traditional power electronics package structure [8]

a) The baseplate is a metal plate, usually made of aluminum alloy or copper. It is a mechanical support for DBC (see below) and power semiconductor components and facilitates the evacuation of heat they generate.

b) The DBC, or “direct-bonded copper,” is an insulating substrate consisting of a very thin ceramic (usually alumina or aluminum nitride) 250 μm to 2 mm thick [7], covered on both sides with layers of copper approximately 300 μm [9]. The top copper layer is patterned for power module electrical interconnections. Semiconductor chips and other components, such as thermal sensors, are soldered directly onto the top copper layer, while the bottom layer is soldered directly to the baseplate.

c) Solder paste is a mixture of solder particles (usually a lead-free alloy of tin, silver, and copper) and flux [7]. It is used to solder semiconductor chips, connection terminals, and other components to the DBC substrate.

d) From one to several, the power transistors (IGBT, MOSFET, etc.) and power diodes form the power module switch, switching cell, or inverter legs.

e) Bonding wires are generally made of gold, aluminum, or copper [10]. They are used to electrically connect the front-side terminals of semiconductor chips to the conductive tracks on the DBC substrate to transfer driving and power signals.

f) Silicone gel is an encapsulating material to protect semiconductor chips and other sensitive components from mechanical shock, moisture, and contaminants. However, it also offers excellent dielectric strength on the surface of DBC’s power devices.

g) Terminals are electrical connectors that link the power module to external circuits. Generally made of copper or aluminum, they are designed to withstand high currents. There are two types: control terminals and power terminals.

h) Plastic case and frame: They protect the internal components from mechanical damage, electrical shock, and the external environment (dust, humidity, O₂, etc.). Both are generally made of glass-fiber-reinforced plastic [7].

Table I below summarizes all the materials used in manufacturing the type of power modules under investigation, considering the data provided by Nordelöf et al. (2019). It is important to note that this description remains traditional and that many variants are possible regarding materials, manufacturing processes, and physical implementations.

Parts	Materials	Coating /plating
DBC	Cu, Al ₂ O ₃	Ni
Baseplate	Cu	Ni
DC terminals	Cu	Ni, Au
Power terminals	Cu	Ni, Zn
Wire bondings	Cu	X
Frame and lid	PPS	X
Screws and washers	Steel	Zn
Solder	95.5Sn3.8Ag0.7Cu	X
Encapsulant	Silicone gel	X

Table I: Material content of the power modules

2 – Key parameters

There are several types of physical implementations of power modules depending mainly on the application, how they are connected to the cooler on the bottom side, and how the electrical interconnections on the top side are made. These may drive significant differences in manufacturing inventory. Therefore, defining the power module type we have considered is necessary. Although the methodology presented here is compatible with any power module, this paper is dedicated to the manufacturing inventory of regular power modules illustrated in Fig. 2 above and Fig. 3 below. It can be seen that this type of power module has top-side screwed electrical interconnects for power interconnects and wired or soldered driving signal interconnects. The bottom side is flat and can be connected to a heat sink for air or water cooling.



Fig. 3. Picture of a traditional IGBT power module considered in this work. [11]

Depending on the type of power module topology (single switch, single switching cell, single leg, multiple switching cells, multiple legs...), there are numerous dimensions and numbers of dies, interconnects, etc... To develop a parametrized manufacturing inventory, it is necessary to identify which parameters play a key role in the dimensions of each part/material of the power module. This will allow us to create the most

precise model while avoiding the laborious task of opening, disassembling, and weighing every part/material. A critical characteristic of our inventory model is that it can be derived mainly and possibly entirely from the characteristics available from the manufacturer datasheets. Below are listed all the parameters that are important and will be used in our inventory model:

- Baseplate dimensions length, width, and height: Lbp, Wbp, Hbp
- Lid Height: Hlid
- Number of power dies: Npdx, with x the power die type number
- Number of power and control signal terminals: Npt, Ncst

The baseplate, as the most significant contributor to the power module's weight, and the plastic lid, another essential component, are both critical inventory parts for ensuring inventory accuracy. Additional parameters can be extracted easily from the manufacturer datasheets if more precise manufacturer inventory is expected:

- Number and diameter of base plate holes: Nhbp, Dhbp
- Length, width, and hole diameter of the power terminals: Lt, Wt, and Dt

Some specific parameters remain difficult to derive only from the manufacturer datasheets. Among the most significant, because they are large manufacture inventory contributors, we have identified the following:

Some power modules have variable casing thicknesses, which can only be measured with a device opening. If an opening is not an option, we propose considering two options: default constant or variable casing thickness.

Also, the silicon gel filling rate is essential because the inner part of the power module is not always filled with silicon gel. Again, it is difficult to derive the appropriate value without the power module opening. Based on experiments, a default value will be used in our model.

The material, the type, and dimensions of the different power die inside the PM are the last essential parameters that have a significant impact on the manufacturing inventory of the power module (different dies can be used, with other dimensions (Ldx, Wdx, Hdx, x being the die type number)). It is well known today that the semiconductor type significantly impacts the die manufacturing inventory [12] while not significantly impacting the manufacturing inventory of the power module's packaging as

long as thermal limits for the package are comparable which is today the case. Moreover, packaging is dependent on electrical die parameters. Therefore the power module manufacture inventory must consider, to some extent, electrical parameters, for example for the current ratings of the isolation voltage ratings. It is out of the scope of this paper to provide a parametrized manufacturing inventory of the power dies considering the type of semiconductor and the type of device (diode, transistor, thyristor, sensor, etc.). In the frame of this research work, we propose to use the inventory values available from the Ecoinvent3 database for silicon-based power devices with a constant thickness and a total semiconductor component surface that is proportional to the size of the DBC, which is also dependent on the size of the baseplate (see modeling part).

The main parameters presented here will determine the numbers and dimensions of all the other power module parts/materials, such as the DBC, the frame, the wire bonding number, and the length.

Inventory data collection and modeling

1 – Design experiment

The objective of this part is to obtain a comprehensive material inventory that can be employed for LCA of diverse power modules, encompassing other pertinent factors or parameters.

The design of the experiment consisted of disassembling two different power modules from two different manufacturers with the same top-bottom-side electrical and thermal interconnects. Further disassembly of power modules is planned as this article is being written. The two power modules dismantled were a Semitrans 3 [11] from the manufacturer and supplier Semikron, with the following specifications: 1200 V, 150 A, and used in various industrial and automotive applications, and a Dynex [13] by manufacturer Dynex Semiconductor Ltd, with a specification of 3300V, 100 A, used for applications similar to Semitrans 3, but for high power applications such as railway traction. The data collected during the disassembly processes comprised three distinct categories: mass, surface area, and time. The file linked in [14] presents the disassembly steps followed for the two PMs. The images in Fig. 4

below illustrate the disassembly work and steps carried out on a Semitrans 3 power module.

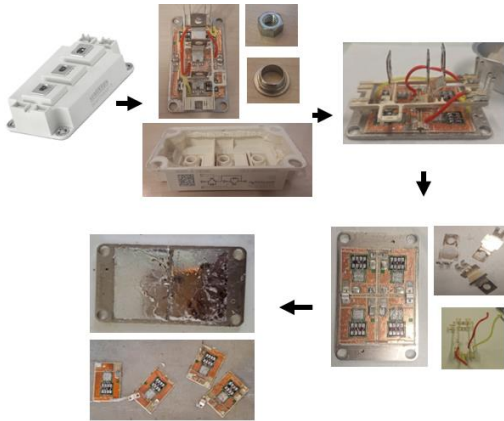


Fig. 4: Disassembly steps illustrated for the Semitrans 3. All collected masses are listed in Table II below.

Part Mass share [%]	Semitrans 3	Dynex
DBC	8,2	9,7
Baseplate	54	30,6
Dies	0,2	0,4
Lid	16,4	38,4
Frame	1,6	3,3
Power terminals	5,9	5,2
Auxiliary terminals	0,8	0,3
Wires bond	0,1	0,5
Silicone gel	8,3	9,8
Screws and washers	3,4	0,7
Solder	0,9	1,2
Total mass	297,9 g	484,3 g

Table II: Mass share measured for the two PM

The manufacturing LCI model has been derived from these collected data and is presented in the next section.

2 – Geometric parametric model and modeling hypothesis

PM manufacture inventory model is described in this section. We can pinpoint the entry parameters from the previously identified data for our model. Those parameters principally consist of length, width, height, diameter, and number of items. The main input parameters presented in section 2 are related to baseplate dimensions, the number of power and control signal terminals, and the number of power devices derived from PM topology. From them are derived most of the other PM elements with the following equations:

Equations	Number
$L_{dbc} = L_{pb} - 2 \times y$	(2)
$W_{dbc} = W_{bp} - 2 \times w$	(3)
$L_{fr} = L_{bp} - 2 \times z$	(4)
$W_{fr} = W_{bp} - 2 \times u$	(5)
$V_{sgmax} = (L_{lid} - T_{lid}) \times (W_{lid} - T_{lid}) \times (H_{lid} - T_{lid})$	(6)
$L_{pt} = H_{lid} + g$	(7)
$L_{pd1} = (S_{dbc} / 0.95 / 4 / 1.5)^{0.5}$	(8)
$L_{pd2} = (S_{dbc} / 0.95 / 4 / 3)^{0.5}$	(9)
$N_{pdwb1} = (L_{pd1} - 2 \times a) \times N_{pd1}$	(10)
$N_{pdwb2} = (L_{pd2} - 2 \times a) \times N_{pd2}$	(11)
$L_{pdwb1} = 1.25 \times L_{pd1}$	(12)
$L_{pdwb2} = 1.25 \times L_{pd2}$	(13)
$L_{cswb} = L_{bp} / 2 - b$	(14)
$L_{senswb} = L_{bp} / 2 - b$	(15)

Table III: Modeling equations for the power module

In (2) and (3), y and w account for the space between DBC and baseplate edges, as illustrated by Figure 5 below. Both are derived from the averaged dimensions collected from PM disassemblies.

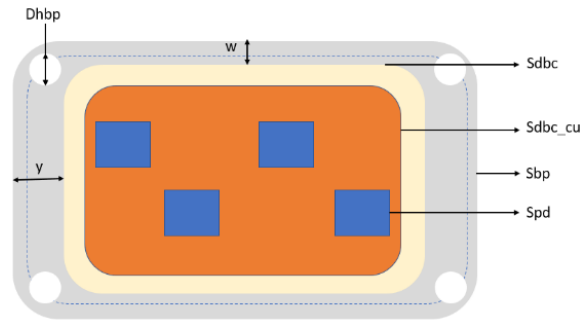


Fig. 5: Schematic of geometrical parameters of baseplate and DBC.

Coming from [7], DBC dimensions are derived: The DBC copper surface before etching is 95% of the DBC surface and 85% after.

S_{dbc_cu} represents the surface of copper on top of the DBC.

DBC dielectric layer thickness is:

$$T_{dbc_dl} = 2 \cdot 10^{-3} \text{m}$$

DBC copper layers thickness is:

$$T_{dbc_c} = 3 \cdot 10^{-4} \text{m}$$

The length and width of the lid are derived from the dimensions of the base plate, while the thickness and height are derived from averaged experimental measurements:

$$L_{lid} = L_{bp}$$

$$W_{lid} = W_{bp}$$

$$H_{lid} = 3,2 \cdot 10^{-3} \text{m}$$

$$T_{lid} = 20 \cdot 10^{-3} \text{m}$$

The top of the surface of the lid may be filled in with extra materials. In this case, the thickness of this surface is modified as follows:

$$T_{lid-extra} = 8 \cdot 10^{-3} \text{m}$$

In (4) and (5), frame dimensions are derived from baseplate dimensions and averaged experimental measures such as z and u , accounting for the distances between the frame and the baseplate edges.

$$T_{fr} = 3 \cdot 10^{-3} \text{m}$$

T_{fr} represents the thickness of the frame.

Lid and frame materials are derived from [7] with the following composition:

68,5% of PPS

28% of fiberglass

3,5% of diantimony trioxide

In equation (6), the maximum volume of silicone gel inside the lid, V_{sgmax} , is derived from the lid dimensions and a filling ratio FR_{sg} coming from experimental measurements:

$$FR_{sg} = 35\%$$

In (7), control signal terminal dimensions are all derived from averaged experimental measures:

$$L_{ast} = 28 \cdot 10^{-3} \text{m}$$

$$W_{est} = 3 \cdot 10^{-3} \text{m}$$

$$T_{cst} = 5 \cdot 10^{-4} \text{m}$$

$$g = 34 \cdot 10^{-3} \text{m}$$

L_{cst} , W_{est} , and T_{cst} represent the control signal terminals' length, width, and thickness, respectively. g represents the length of the bent part of the power terminal on the top of the lid.

Power terminal dimensions are all derived from averaged experimental measures:

$$W_{pt} = 12 \cdot 10^{-3} \text{m}$$

$$T_{pt} = 1,3 \cdot 10^{-3} \text{m}$$

L_{pt} , W_{pt} , and T_{pt} are the power terminals' length, width, and thickness, respectively. g is the length of the bent part at the top of the power terminal.

The total semiconductor surface area is derived from averaged experimental measurements. It is based on the ratio of the pre-etched DBC top copper layer area to the total semiconductor area. The average value of this ratio is approximately 4, rounded to 4. This estimate is only valid for silicon-based semiconductors. Therefore, their dimensions can be derived depending on the type and number of semiconductors. Dies are considered to be square. Types 1 and 2 are for

transistors and diodes, respectively. Diodes are considered half the area of transistors.

In (8) and (9), S_{dbc} is the total surface of the DBC, with L_{pd1} and L_{pd2} representing the lengths of the power transistors and diodes, respectively.

It should be noted that this part of the model is rough and not very accurate. It would be much better if a power module could be opened to check the dimensions of the dies. Nevertheless, it provides a logical estimate as the size of the power module is roughly proportional to the size of the dies.

For the solder used in the PM, a thickness was taken from the literature (Sunday E. *et al.*, [9]):

$$T_{sld} = 1 \cdot 10^{-4} \text{m}$$

In equations (10) (11) (12) (13), N_{pdwbx} , L_{pdwbx} , and D_{pdwbx} are the number, length, and diameters of the wire bondings connected to the top-side power of each type of power device. 1,25 accounts for the shape of the wire bondings, and N_{pd1} and N_{pd2} account, respectively, for the number of power die types 1 and 2.

$$D_{pdwb1} = D_{pdwb2} = 180 \cdot 10^{-6} \text{m}$$

$$a = 1,5 \cdot 10^{-3} \text{m}$$

Figure 5 illustrates parameter a .

Regarding the wire interconnects for the control signal and, eventually, the thermal sensor, the following model is derived from experimental averaged results:

$$D_{cswb} = 180 \cdot 10^{-6} \text{m}$$

$$N_{cswb} = N_{cst}$$

$$N_{senswb} = 0 \text{ or } 2$$

Figure 5 illustrates the position of the control signals and the parameter b to explain the equations better.

$$b = 5 \cdot 10^{-3} \text{m}$$

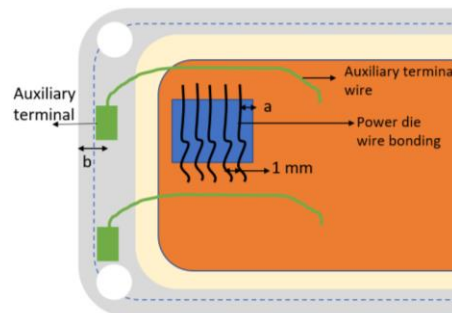


Fig. 5: Schematic of geometrical parameters of wire on power dies and auxiliary terminals.

Dscrw and Tscrw, respectively, the diameter and the width of the screws, are all derived from averaged experimental measures.

$$Dscrw = 6 \cdot 10^{-3} \text{ m}$$

$$Tscrw = 5 \cdot 10^{-3} \text{ m}$$

Nscrw depends on the number of power terminals on the top of the lid, which is usually 3.

The total number of washers on the PM is either 0 if there are no washers or 4. The diameter and thickness are both derived from averaged experimental measurements.

$$Dwsh = 6 \cdot 10^{-3} \text{ m}$$

$$Twsh = 4 \cdot 10^{-3} \text{ m}$$

The length and width of the silicone adhesive are derived from those of the lid, and the thickness is derived from averaged experimental measures.

$$Tslc = 6 \cdot 10^{-4} \text{ m}$$

From [7], all of the power module's parts and materials are listed in Table 1.

3 – Implementation of the inventory flows

After collecting material data through disassembly and measurements, we have defined our model's input parameters. Using these geometric parameters, we can calculate surfaces and masses using material densities. The next step presented in this section is extracting manufacturing process data, as an example illustrated in Figure 6 below from Nordelöf A. et al. [7], and implementing our inventory flows.

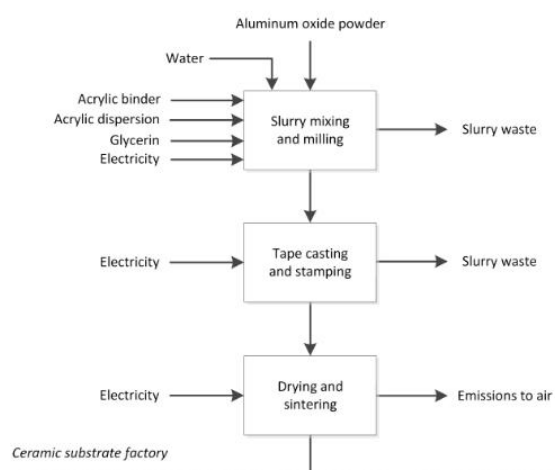


Fig. 6: Manufacturing process data for ceramic substrate production (Nordelöf A. et al., [7]).

[7] provides reference quantities from the literature, from which we can calculate the appropriate scaled amount.

The 'scaled amount' reduces the reference quantities used for a single unit to the quantity needed to manufacture our product. This scaled quantity depends on our input geometric parameters. Moreover, the sources from which the reference quantities are derived are given and linked to the Ecoinvent 3 database.

For example:

According to [7], 1.92 kg of alumina is needed to manufacture 1 m² of ceramic substrate [15]. The scaled amount can be calculated using the value of Sdbc, which was determined in the previous section.

Inventory model validation

We derived all inventory elements from input parameters and checked the results to assess if our power module manufacture inventory is satisfactory.

Table IV below presents the input parameters considered for one of the power modules and the error concerning the elements measured during the PM disassembly.

Substances	Estimated mass [g]	Measured mass [g]	Deviation (%)
Copper(baseplate, terminals,wires)	181,9	181,5	0,2
Doped silicon	0,8	0,7	11,2
Solder	3,2	2,6	23,7
Low-alloy carbon steel	8,9	10,1	11,8
Plastic	61,3	53,9	13,8
Silicone gel	31,2	24,7	26,1
DBC	23,7	24,4	2,8

Table IV: List of the values for the manufacturing inventory model input parameters and their corresponding deviation for the Semitrans3.

The weighted deviation is calculated using the following equation:

$$WD = \frac{\sum (\text{deviation} * \text{measured masses})}{\sum (\text{measured masses})} \quad (16)$$

This leads to the following weighted deviations:

- Semitrans 3: 5,6%
- Dynex: 7,5%

We can make further comparisons with our model using the total mass collected from the respective datasheets of Dynex and Semitrans 3.

Power Module (unit g)	Total mass datasheet	Total mass measured	Total mass estimated
Semitrans 3	325	298	315
Dynex	500	484	491

Table V: Total masses comparison

Suppose the total and estimated mass are significantly different. In that case, the user should pay attention to the material content of their baseplate, as this particular piece can cause many errors.

These deviations are considered satisfactory for a first step in our work. However, to make the PLCI more precise from our work perspective, more power modules, such as soldered or press-fit, should be disassembled.

The PLCI is not geographically limited as the process data used respects the same limitations as Nordelöf A. et al.'s (2019) work. An important point is that the inventory can be modified to account for different power modules, making it suitable for different LCA analyses. It could also be used in eco-design methods to support PM design while considering the environmental impacts of LCA. The PLCI model could be used with existing LCA tools, such as Brightway, which uses a Python environment good for parametrization, as done in the article written by Li et al. (2025) [16].

Conclusion

This paper has presented a model for the manufacturing inventory of a specific type of power module. The model was derived from the experimental disassembly of the different PMs, which measured and weighed all elements. Completed with data from the literature, the inventory model has been developed. It has been successfully compared to experimental values, with ponderation errors in the range of 6%. It is now ready to be used for LCA analysis, as it is described in [ref]. It is expected to improve the model with additional data collected from experiments and consider different power module types.

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