A Scalable Life Cycle Inventory of an Automotive Power Electronic Inverter Unit
Technical and Methodological Description, version 1.01

ANDERS NORDELÖF
MIKAEL ALATALO

Department of Energy and Environment
Divisions of Environmental Systems Analysis & Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2018
Report No. 2016:5 (1.01)
A Scalable Life Cycle Inventory of an Automotive Power Electronic Inverter Unit
Technical and Methodological Description, Version 1.01

ANDERS NORDELÖF
Division of Environmental Systems Analysis
Chalmers University of Technology
anders.nordelof@chalmers.se

MIKAEL ALATALO
Division of Electric Power Engineering
Chalmers University of Technology

Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, 2018
A Scalable Life Cycle Inventory of an Automotive Power Electronic Inverter Unit
Technical and Methodological Description, version 1.01

ANDERS NORDELÖF & MIKAEL ALATALO

© ANDERS NORDELÖF, 2018.

Report 2016:5 (1.01)
Division of Environmental Systems Analysis
Chalmers University of Technology
412 96 Gothenburg
Sweden
Phone + 46 (0)31-772 1000
Context

This report is one of three coupled publications. It describes the technical and methodological selections, and the data collection made to develop a scalable life cycle inventory (LCI) model of an automotive power electronic inverter unit. It follows the same structure and in parts also repeats the background information and description of methodology which was co-developed in a related project covering a scalable LCI model of an automotive electric traction motor (Nordelöf et al., 2017). It is a part of a yearly report series published by the division of Environmental Systems Analysis at Chalmers University of Technology, originally numbered for release during 2016 but finalized and published for the first time during 2017.

The report presents theoretical background and data collection procedures of the scalable LCI model and it is intended to be used as a reference book by the model user when detailed information and explanations are sought. For that reason, no summary or abstract was included.

The scalable LCI model covers both design and production data of an inverter unit intended for to control a typical electric vehicle propulsion motor. The resulting LCI model, in the form of a Microsoft Excel Macro-Enabled Worksheet file (Nordelöf, 2018), can be downloaded from the Swedish Life Cycle Center as a part of the SPINE@CPM LCA Database1.

Two peer reviewed articles are also published about the LCI model in parallel with this report. The first article, part I (DOI: 10.1007/s11367-018-1503-3), describes how the LCI model was established and the type of results it provides. It includes a description inverter unit design and the LCI data model structure, based on chapters 2 and 4 of this report. Additionally to what is included here, it also contains an evaluation of the mass estimations made by the model through comparison with data for 10 inverter units intended for use in vehicles, based on supplier’s technical information published from 2013 or later.

The second article, part II (DOI: 10.1007/s11367-018-1491-3), presents an overview of new primary production data and how data has been compiled to cover the complete inverter unit manufacturing chain, including the power module fabrication, a factory for assembly of printed circuit boards and automotive power electronic units. More in depth information about these production procedures, and how the data was established, is described in Chapter 5 of this report. Part II of the article series also discusses the selected system boundaries and explains how to link the gate to gate inventory to the Ecoinvent database version 3 (Weidema et al., 2013), based on Chapter 2 of this report.

---

1 Provided by the Swedish Life Cycle Center at http://cpmdatabase.cpm.chalmers.se
Revision history

Version 1.01 is the second release of the report. Changes compared to version 1.0 include:

- Addition of DOI-links to published articles in the context summary
- Minor corrections in text and tables of chapters 4 and 5
- Inclusion of Appendix C
# Table of Contents

Context ........................................................................................................................................... iii

Revision history ............................................................................................................................ iv

1 Introduction.................................................................................................................................. 1
  1.1 Background ............................................................................................................................ 1
  1.2 Purpose and intended application of the inventory model ..................................................... 1
  1.3 Aim and structure of this report ............................................................................................ 2

2 Methodological approach .......................................................................................................... 3
  2.1 Model structure, data collection and scaling ......................................................................... 3
  2.2 Assessment system boundaries ............................................................................................. 6
  2.3 Representation of flows in Ecoinvent ..................................................................................... 6
  2.4 User options, technical scope and uncertainty ....................................................................... 7

3 Technical overview .................................................................................................................... 9
  3.1 Automotive power electronic converter categories and their applications .......................... 9
  3.2 Power semiconductor devices .............................................................................................. 10
  3.3 The main building blocks of an inverter unit .......................................................................... 11
  3.4 Power rating and the importance of cooling ......................................................................... 13
  3.5 Integrated packaging and variability in design ....................................................................... 15
  3.6 Other transistor types and new materials ............................................................................. 15

4 Design and representation of the inverter unit ........................................................................ 17
  4.1 Electronic subparts ................................................................................................................. 17
    4.1.1 Baseline data and general arrangement of reference units ............................................. 17
    4.1.2 Power module design and principle for scaling ........................................................... 17
    4.1.3 DC link capacitor design and principle for scaling ....................................................... 22
    4.1.4 Driver board .................................................................................................................. 25
    4.1.5 Logic board ................................................................................................................... 27
  4.2 Casing, cooling and uniting parts .......................................................................................... 29
    4.2.1 General description and data for the housing compartment ........................................ 29
    4.2.2 Liquid cooled heatsink ................................................................................................ 30
    4.2.3 Air cooled heatsink ...................................................................................................... 31
    4.2.4 Casing surface coating ................................................................................................ 33
    4.2.5 Laminated bus bar ....................................................................................................... 34
    4.2.6 Cable glands ................................................................................................................ 38
    4.2.7 Screws, washers and spacers ...................................................................................... 39
Assessment of production procedures

5.1 The production of electronic subparts
  5.1.1 Semiconductors chips for the power module
  5.1.2 DC link capacitor
  5.1.3 Production and assembly of printed circuits boards

5.2 Manufacturing of copper, brass and steel subparts
  5.2.1 General processing of copper and brass parts
  5.2.2 Production efforts for steel parts
  5.2.3 Electroplating of metal surfaces

5.3 Preparation of plastics and elastomers
  5.3.1 Molded parts in the power module and glands
  5.3.2 Extruded foils, spacers and rubber seals
  5.3.3 Bus bar lamination process

5.4 Aluminum casing production
  5.4.1 Overview
  5.4.2 Die casting
  5.4.3 Machining
  5.4.4 Spray painting
  5.4.5 Anodizing

5.5 Power module fabrication
  5.5.1 Overview
  5.5.2 Ceramic substrate fabrication
  5.5.3 Direct copper bonding
  5.5.4 Etching of the conducting pattern
  5.5.5 Soldering the power module
  5.5.6 Mounting the frame and potting
  5.5.7 Bonding of wires and terminals
  5.5.8 Cleaning steps in the power module assembly

5.6 Assembly and building services
  5.6.1 Mounting parts into a complete unit
  5.6.2 Technical building services

References

Appendix A: Driver board component classification
Appendix B: Logic board component classification
Appendix C: Qualitative uncertainty assessment
1 Introduction

1.1 Background

Exhaustive and transparent inventory datasets for electric vehicle (EV) powertrain components are lacking, both regarding the composition of materials and production processes (Hawkins et al., 2012). Existing datasets are often derived from components with a specific set of performance parameters corresponding to a certain mass and material composition, but presented and used as if scalable on mass basis (i.e. per kilogram of component) (Del Duce et al., 2014, Weidema et al., 2013). However, any variation of powertrain requirements implies a modification of the component’s dimensions and design, i.e. changes in terms of weight and composition of the subparts. In electronics, changes in performance characteristics are typically not linearly related to the complete part mass, as unit processes otherwise commonly are expressed in life cycle inventory (LCI) data. Consequently, even when size-adjustments made on power electronic components during LCA modeling are based on appropriate properties, such as the rated power capability, this can lead to errors and unrealistic results if the scaling is conducted on a typical unit process datasets covering a complete power electronic component, exemplified by Hawkins et al. (2013a), (2013b).

Instead, useful and flexible cradle-to-gate LCIs of automotive components, including upstream production efforts, preferably build on relatively detailed data for weight and composition, where the scaling of different subparts or constituents of subparts can be modeled differently: remaining constant, changing linearly but with different coefficients, or higher order nonlinear relationships. Still, the combination of detailed material compositions and performance data is difficult to obtain. Other engineering parameters are more easily acquired, for example the rated peak power of the electric motor and the nominal operation voltage level of the battery, in open automotive powertrain specifications or information brochures.

Hence, there is lack of LCI data for power electronics which can be more accurately calculated from basic parameters in open specifications. In response to a similar data gap, a scalable LCI model of an electrical automotive traction machine was developed in a preceding and related project (Nordelöf et al., 2017). The need for easily generated inventory data for automotive power electronic inverter units called for additional data collection in this project.

1.2 Purpose and intended application of the inventory model

The goal of this project has been to establish a general and scalable LCI data model for a DC/AC power electronic inverter unit, designed to control an EV propulsion motor. The aim was to provide mass composition and manufacturing data for a representative design. The model generates data on inverter units ranging 20-200 kW in nominal power and with a DC link voltage of 250-700 V, i.e. suitable for a small passenger EV up to, for example, a small electrically propelled city bus or truck (Volvo, 2015). Another important aim was to make the model build on easily accessible parameters. Accordingly, if no other specific information is available to the model user, it is expected that the rated nominal value of the inverter match the peak rating of the electrical machine (see Section 3.4 for a more detailed discussion). Similarly, the voltage of the DC link is provided by the battery (although the system design can include voltage converters, see sections 2.4 and 3.1). Hence, as for power, if no information is available about the voltage rating of the inverter unit or different voltage levels specified for the DC system, the model input can be matched with the nominal operating voltage of the battery.

An overall purpose of the model is to complement the few existing datasets and assist LCA evaluation of electric powertrains through generation of data for inverter units with varying size. The resulting datasets represent a gate-to-gate production of the inverter, from materials to complete unit (printed circuit boards and surface mount board components are modeled as ready-made input). The inventory model is available as a spreadsheet file in Microsoft Excel, which can be downloaded from the SPINE@CPM LCA Database², together with this report.

The inverter unit mass and material composition presented by the model is generated by scaling the different subparts individually based on the user input. The result can be used as an estimate of any automotive AC traction motor controller if it falls within the range for power and battery voltage requirements for which

---

the model is valid. Specific design selections were adopted for a stand-alone inverter unit. The manufacturing data is presented in such a way that the data can be used in its own right, in addition to being used as a part of the data model, for example in LCA studies involving the same productions steps for other electronic products.

Finally, an important objective of this project was to make the model easy to use by LCA practitioners. For this reason, all manufacturing processes were followed upstream to a point where LCI data for input flows to the model are available in version 3 of the Ecoinvent database (Weidema et al., 2013), i.e. in the form of low voltage electronic board components, printed circuit boards (PCBs) and material production data etc.

1.3 Aim and structure of this report

The aim of this report is to explain and describe the theory and data processing that has led to the inventory details presented in the spreadsheet model file coupled to this report. It is expected that the target audience (typically LCA practitioners) have basic engineering knowledge but little or no experience of power electronics. The report has been divided into four chapters after this introduction. Chapter 2 discusses the working procedures and the LCA methodology behind the model; Chapter 3 presents basic terminology and theory of power converters, especially inverters; Chapter 4 explains the design selections in detail and the resulting composition of the unit; and Chapter 5 describes the necessary assembly and subpart production procedures along with the LCI data collection for each process. There are also two appendixes (Appendix A and B) presenting the board component classification made for the two PCBs.


## 2 Methodological approach

### 2.1 Model structure, data collection and scaling

This project was conducted as a collaboration between researchers with different expertise, both LCA methodology and design of power electronics. Component design data was compiled from: material content declarations, theory books, technology benchmarking literature, experts in industry, and product descriptions. Additionally, production data has been collected from industry in the form of production site documentation, several site visits, expert interviews, machine specifications, and textbook descriptions. The compilation resulted in a substantial amount of new original data for LCA of electronics. Still, some data has been reused, or slightly reworked, from the related project report describing the development of a scalable LCI model for an electrical automotive traction machine (Nordelöf et al., 2017). Design and manufacturing data was combined into one scalable LCI model.

The LCI model requests the user to enter values for nominal power and DC system voltage of the inverter unit. In return, it provides a gate-to-gate LCI for the production of the unit, together with its mass configuration and a recommended representation for the input and output flows in version 3 of the Ecoinvent database (Weidema et al., 2013). The basic structure of the LCI model is shown in Figure 1.

The main underlying data has been published by Infineon Technologies AG (2012a, 2014b). It refers to two complete inverter units in terms of electric and electronic function, offered to customers as a HybridKit for evaluation of their HybridPACK™ power transistor modules (Infineon, 2012a, b, c, 2014b). The HybridPACK™ series is a recognized product brand used in several hybrid and battery electric vehicle models from established auto-manufacturers, e.g. BMW, Kia and Hyundai (Green Car Congress, 2011, Ozpineci, 2016). These design descriptions specify the topology, the size of power stage components and the amount of low voltage electronics necessary to build functioning units. Additional data was gathered for detailed material configurations of the power stage subcomponents, i.e. the power module and the DC link capacitor (for an explanation of these subparts, see Section 3.3). The principal design was judged to be satisfactorily generic for the LCI model, based on observations of other inverter units for automotive traction applications made in benchmarking literature and textbooks (Sheng and Colino, 2005, Burress et al., 2011, Volke and Hornkamp, 2012, Burress and Campbell, 2013, Miller, 2013b, Ozpineci, 2014, Mitsubishi, 2014, Fuji Electric, 2015).

Nonetheless, in order to model a full stand-alone inverter unit several additional passive parts had to be included: a housing compartment and cooling heatsink (manufactured in one piece, referred to as the casing), a laminated bus bar for power distribution, and connectors suitable for in-vehicle operation. Consequently, the data from Infineon (2012a, 2014b) was combined with data for catalogued subparts and engineering estimates to fulfill all specified device requirements.

---

**Figure 1: Structure of LCI model.**
The model build on parameters provided in automotive powertrain specifications: the rated nominal value of the inverter (assumed to equal the peak rating of the electrical machine), and nominal DC link system voltage (equal to the nominal operating voltage specified for the battery). The baseline data from Infineon (2012a, 2014b), as well as all additional data collection, was found valid for modeling and rescaling the inverter unit within a power span of 20-200 kW and a voltage span of 250-700 V.

It was observed that there is an overall correlation between the size of the inverter unit and its power capability (Fuji Electric, 2015, 2016, Infineon, 2012a, 2014b). Consequently, power was selected as a main scaling parameter. However, various subparts grow in different ways with increasing power demand. Geometrical dimensions have to be larger to handle higher currents, for example in conductors, or simply because surrounding parts are expanding in size. At the same time, other subcomponents can remain essentially unchanged to fulfill their dedicated functionality. As a main strategy, data was gathered to allow linear scaling of mass with increasing power demand, per material constituent of all included subparts, i.e. each material is scaled with a dedicated coefficient in relation to the specified nominal power based on two well-defined reference design data sources within the model span (at 20 kW and 80 kW, the for two reference units). In order to do this, it was necessary to sort some elements in the original material declarations (referred to as the baseline data or baseline units) into relevant substance groups and assign them common scale factors, for example in the case of solder. This main strategy was applied on the power module, the aluminum casing, cable glands and uniting parts, i.e. screws, washers and spacers.

For the two PCBs containing the drivers and logic control of the power module, very little (driver board) or no (logic board) correlation was found between the size and the power capacity (see sections 4.1.4 and 4.1.5). Therefore, to keep the model simple, these PCBs are modeled as constant, i.e. with the same board size and the same number of board components over the entire span of model parameters. This also includes the large signal connector for external communication.

Oppositely, the scaling of the DC link capacitor and the laminated bus bar is more complex. For capacitors it was observed that they generally become larger and heavier, and feature higher capacitance, with increasing power demand, but the change in size also relates to the DC system voltage rating (see Section 4.1.3 for an explanation of theory and details about the scaling). Likewise, the DC and AC conductors in the laminated bus bar must have certain cross sections in order to handle high currents. Typically, the cross section is determined by a rule of thumb from the maximum allowed current (Mersen, 2013). At the same time, conductor lengths are decided by the geometry of the complete inverter unit. As a result, both DC and AC circuit theory, and lengthwise scaling of the conductors, were used to sort out how the total bus bar size can be adequately estimated from the input of power and voltage (see Section 4.2.5 for details).

For the scaling of the design it is important to note that the parameterization to nominal power capability in the model (with start values and scale factors for each substance, or group of substances), was possible because of the combined availability of mass and material configuration data for the two Infineon baseline inverter units, and their stated nominal power rating at 20 kW and 80 kW, respectively. In the case of the DC link capacitor, the complete component mass is scaled with one scale factor multiplied with the quotient of the two parameters (power and voltage) while the configuration is fixed (see Section 4.1.3). The scale factor was established from plastic four film type capacitors where mass, voltage rating and power rating were known.

In the model file, there is also a maximum power value presented for the inverter unit, calculated as 150% of the nominal value provided by the user. It was chosen as a rough but reasonable indication of the power capacity during a short thermal overload. As regards cooling, there are both air and liquid cooled heatsinks included in the model. They build upon heatsink design proposals established to provide sufficient cooling for the reference inverter units during continuous operation in various ambient temperatures. However, the scaling range for the air cooled heatsink option was delimited to 20-50 kW, since outside this span it became too large and unrealistic in size compared to the housing compartment (the casing was modeled in two segments: a heatsink and a component compartment, see Section 4.2.1).

Subsequently, the result from the design calculations of the model is combined with unit process datasets established for the manufacturing stage. They describe how the inverter unit is produced from an input mix of ready-made subparts (i.e. the PCB and board components) and material constituents (for example the power module, the laminated bus bar, cable glands etc.). The data collection for the production of subparts was based on a variety of sources: mainly literature – articles, various reports and textbook descriptions – but also expert interviews.

Data for the mounting of the PCBs to fulfill automotive requirements was gathered from the manufacturing facilities at Aros Electronics AB (Aros, 2013, 2014a, b, c, d, e, f, g, Edgren, 2014, 2015, 2017, Welin, 2014a, b). The company designs and assembles PCBs and inverter units for control of electric machines in the power range of 0.1-30 kW, both for automotive and other industry. Production volumes are around
250 000-300 000 assembled PCBs and 125 000-150 000 inverter units per year (Aros, 2014e, Edgren, 2017). Data from Aros was also used for the final assembly of the complete inverter unit and the general account of technical building services.

Figure 2: Overview of the technical system boundaries for the collected production data, including different main information sources, and how the LCI model relates to the Ecoinvent 3 database (Weidema et al., 2013).
2.2 Assessment system boundaries

The LCI model provides mass and manufacturing data for one automotive inverter, as delivered at the factory gate. The functional unit is one power electronic inverter unit intended for controlling electric vehicle propulsion motors, with specific power and voltage requirements. It is a gate-to-gate LCI with input of ready-made components or various stages of material processing, with reference to datasets available in Ecoinvent version 3 (Weidema et al., 2013). No use or end-of-life treatment has been included and it is possible to combine the inventory with input data for virgin raw materials just as well as recycled materials. An overview of the technical system boundaries are shown in Figure 2.

As regards geographical system boundaries, the intention has been to keep the model as flexible as possible for the user and representative on a global level. No specific countries, regions or sites have been defined for the production steps. For example, all input electricity has been marked as “optional” for the user in terms of the production source or market mix.

Nevertheless, it can be noted that the two baseline units describe technology of Infineon Technologies AG, a German electronics manufacturer with global operations, mainly situated in Europe, North America and Asia (Infineon, 2012a, 2014b). The data for the DC link capacitors also comes from global companies with headquarters in Europe and the USA (Epcos, 2017, Kemet, 2017). The primary literature sources for the power module design and manufacturing were provided by German (Volke and Hornkamp, 2012) and North American text books (Sheng and Colino, 2005), whereas general practices in PCB and inverter unit assembly, as well as building services, were gathered from a Swedish electronics manufacturer (Aros, 2016). Summing up, both design and manufacturing data represent state-of-the-art technology of industrialized countries.

For the scale of production, the model represents high volume manufacturing to the largest extent possible. This is especially important in all datasets which build on a combination of data or where the original data has been reworked, for example the electricity use of a furnaces per sample. In such cases, as a general principle, the throughput was modelled to represent a full production load. In essence, this results “best estimate” for the energy consumption per sample, but it was judged as the most consistent approach compared to making different ad hoc assumptions for any such occasion.

No transportation of goods are included in the LCI model. Instead, the user is expected to add subpart transportation if it is relevant for the study in which the LCI model is used.

In terms of time, both design and manufacturing data has been judged as representative for the current level of technology. All data measured data from industry has been collected within the last five years. Most technical reports and datasheets, and many research articles are from the same time period, or at least published within the last 10 years. However, in some cases, literature sources are older, if they were judged to remain relevant. The extensive textbook on power modules by Sheng and Colino (2005) is one such example. The archetypical power module design described in their book and it has been very similar since the 1990’s (Tan et al., 2010, Volke and Hornkamp, 2012), despite that development in other areas of electronics have progressed more rapidly (see sections 3.5 and 3.6).

2.3 Representation of flows in Ecoinvent

As mentioned in Section 2.1, and also shown in Figure 2, all raw material input to the inverter unit was traced through upstream manufacturing processes up to a point where existing datasets for the production of materials are available in Ecoinvent version 3 (Weidema et al., 2013). “Linked flows” are provided throughout this report and in the model file, for an Ecoinvent representation of all inputs, wastes and emissions, unless the user is called on to make a more attentive selection. The linked flow is then noted as optional, as already exemplified for the use of electricity in production, see Section 2.2 above. Hence, all throughout chapters 4 and 5, there are descriptions of flows being “listed” or “coupled” to Ecoinvent, and this refers to the recommended database representation of the flow when it passes over the system boundary, see Figure 2. Ecoinvent 3 has been abbreviated to E3 all throughout Chapter 5 in figures and tables. Another abbreviation in the same set of tables is IF, denoting “internal flow” (i.e. a flow not crossing the system boundary).

Furthermore, also shown in Figure 2, there is an extended system boundary which encircles a set of Ecoinvent (Weidema et al., 2013) activities for material transformation and coating. These activities are also included in the LCI model file, but listed separately from the inventory for the charted gate-to-gate model with the regular system boundaries. The reason for this setup is the formulation of material transformation activities in Ecoinvent. The production efforts are analogous to services which reshapes one kilogram of input raw material or semi-finished product into one kilogram of output product (Hischier, 2007, Steiner and Frischknecht, 2007, Classen et al., 2009). In general, in the representation of metal forming, conversion of
plastics and average machine working of metals, the amount of materials removed and scrapped are included as flows in and out of the activities along with other auxiliaries and emissions, but not the materials and products being reshaped. Accordingly, the reference flow of the process refers to the activity and not the output product, also when the reference flow unit is expressed as a mass, see for example the description of “hot rolling” in Classen et al. (2009). Nevertheless, as described in sections 5.2.1, 5.2.2, 5.3.1, 5.3.2 and 5.3.3, a number of these activities in Ecoinvent were identified and included in the LCI model to properly account for the making of several subparts from their material constituents. In order to clarify the inclusion of these “service flows” crossing the ordinary system boundary and avoid confusion for the user, the setup with a separate activity list and the extended system boundary was selected. Moreover, users of the LCI model should be aware that the detailed definitions of these production efforts are not consistent within Ecoinvent version 3 (Weidema et al., 2013). For details about the differences between, for example, the formulation of metal forming activities and those for the conversion of plastics, we refer to the original sources (Hischier, 2007, Steiner and Frischknecht, 2007, Classen et al., 2009).

2.4 User options, technical scope and uncertainty

The model input pop-up window is shown in Figure 3. The user is asked to enter two values: the rated nominal power of the inverter unit and the DC link system voltage. The idea was to base the model on parameters which are easy to access in powertrain specifications. But in fact, technical details about the inverter unit are not always included in open automotive documentation. In such cases, the power rating of the electric motor can be used, since it is the object to which the inverter output power is delivered. Even so, the harmonization of power capability between the electric motor and the inverter may differ between vehicle types (see Section 3.4). Still, if no other information is available, it is recommended to set the requested nominal rating of the inverter unit equal to the peak power rating of the electric motor.

Similarly, the voltage rating of the inverter unit is not always provided as a single value (see section 3.4). Even so, it is the high voltage traction battery of the vehicle that is the original voltage source of the DC link. But in some powertrain configurations the voltage is subsequently boosted to a higher level by a (DC/DC) converter. In such cases, this higher DC system voltage level might be reported in an overall powertrain specification. The aforesaid system voltage can then be used as input to the LCI model. But if no specific

![Figure 3: The LCI model input pop-up window, showing the modeling options for the casing including different cooling, and the laminated bus bar.](image-url)
information is available for the voltage rating of the inverter unit or the DC system voltage, it is recommended to use the nominal operating voltage of the battery.

Furthermore, also shown in Figure 3, the LCI model offers flexibility for the user whether or not to include two subparts with a significant mass contribution: the aluminum casing and the laminated bus bar. Each of these two parts can be excluded separately or both at the same time. For the casing, it is also possible for the user to enter other, alternative mass data.

There were several reasons to include these model options. First, the inverter unit may sometimes be integrated with other parts in a larger casing and with a common, larger bus bar structure. Such a design can now be modeled by deselecting the two subparts. Second, both display large variability in design, for example depending on the packing geometry and cooling. Especially, for the casing there are a number of design parameters which can be varied (see sections 4.2.1-4.2.3). By excluding the casing and model it separately, or by adjusting the casing mass directly in the model, the user can increase the model precision in relation to a specific modeled object, if either the casing mass or the total mass is known. Note that if the casing is excluded from the LCI, the fasteners (screws, plates and nuts) used for the mounting of the casing (i.e. not all fasteners), the cable glands and the casing paint (see below) are also excluded, since these parts are mounted into or applied on the casing and are expected to change in design along with an alternative casing solution. However, fasteners and cable glands (but not the paint) are modeled with the original settings if the casing is included, but adjusted in mass by the model user.

In addition, the casing consists of two sections, a housing compartment and a heatsink. There are two cooling options for the heatsink included in the model: liquid cooling and air cooling. Liquid cooling is valid for the entire model range whereas air cooling only can be selected for a power range of 20-50 kW. More information about the cooling options is available in sections 4.2.2-4.2.3. It is important to note that air cooling requires an active fan mounted in the vehicle, packed in the same compartment as the inverter unit. Such a fan is not included in the LCI model. Similarly, liquid cooling involves an external cooling system with a pump, hoses and a refrigerant. These are also not included.

The two different heatsink options imply different surface treatment of the entire casing, see section 4.2.4 for explanations and details about these model settings. If liquid cooling is selected for the heatsink, then the complete outer casing surface is modeled as painted with a transparent varnish (described in section 5.4.4). Alternatively, if air cooling is selected, then the complete casing is modeled as anodized (see section 5.4.5).

Lastly, the inventory data presented in this report and in the model file have a varying level of uncertainty between different flows. Ecoinvent data is generally provided with uncertainty distributions which can be used to calculate how errors propagate throughout cumulative results using a Monte Carlo simulation tool. Unless data has been collected from a sufficient number of sources to provide a statistical analysis, these uncertainty distributions originate from an evaluation made by the data creator using a pedigree matrix, provided and described by Weidema et al. (2013). Such uncertainty factors were provided for the electrical motor mentioned earlier in sections 1.1 and 2.1, described in Nordelöf et al. (2017), but have not yet been included in the inverter LCI model described in this report. However, following the same setup, the plan is to incorporate uncertainty factors in future updates of the model and to be described in this report by adding an additional appendix.
3 Technical overview

3.1 Automotive power electronic converter categories and their applications

The term converter is general and refers to a circuit that is able to convert electrical energy from one voltage level and frequency to another. The inverter is one of three different converter types which are commonly used in electrically propelled vehicles. The other two are DC/DC converters and on-board chargers. An externally charged all-electric vehicle (EV), or a typical plug-in hybrid vehicle (PHEV), contains at least one converter of each of these three types, often more (Çağatay Bayindir et al., 2011, Emadi et al., 2008). The inverter unit then acts as the electric motor controller, the DC/DC converter as the link between the vehicle’s electrical high voltage system and its low voltage system, and the charger enables charging of the battery, as presented in Figure 4. The number of inverter units in the vehicle depend both on the number of electric motors installed as well as the auxiliary demands. Hybrid electric vehicles (HEVs) without external charging capability also often have at least three converter units, but with a simpler charger (AC/DC rectifier) coupled to the alternator compared to the grid charger. Nevertheless, all vehicle types have a similar path for the electric drive setup, transferring energy from the battery to the wheels (and back during regeneration), also shown in Figure 4.

![Figure 4: Schematic overview of an electric drive system and the most common converter types.](image)

An inverter converts current from DC to AC, which in electrical terminology is called inversion. Hence, it is sometimes referred to as a DC/AC converter. The main application is to control AC driven electrical machines. The unit is then also labeled as an electric motor drive. In motoring mode, the drive converts DC from the battery and delivers a specific AC voltage and frequency to the electrical machine which in turn provides a desired torque to the wheels of the vehicle. During vehicle braking, or ‘regeneration’, the motor drive converts AC back to DC, allowing power to flow from the electrical machine into the battery. Although the unit then acts as a rectifier, the notation is that the inverter is ‘bidirectional’, since the main aim of the design is to drive the motor.

Inverter units are also used to supply power from the DC link to auxiliary AC loads which otherwise would be belt driven in conventional powertrains, such as compressors and pumps coupled to heating, cooling and ventilation. These types of loads are commonly in the range of 5-10 kW but can reach 20 kW depending on the vehicle type and functionality (Emadi et al., 2008). As an example, a vehicle air conditioning system uses about 2 kW at steady-state and up to 5-6 kW at peak load (Husain, 2011). Both single and three phase inverters,

---

3 The abbreviation EV for “electric vehicle” can be used in a broad sense, meaning “any vehicle with electric propulsion”. However, in this text, and in most use (based on the authors experience), it refers to vehicles where all driving is electric, i.e. without any additional propulsion source.
with either metal oxide semiconductor field effect transistors (MOSFETs) or insulated gate bipolar transistors (IGBTs), are used for these purposes (Emadi, 2005, Emadi et al., 2008).

**DC/DC converters** are used in hybrid and EV powertrain configurations mainly for three purposes: to boost the battery voltage if it is too low to provide what the electric powertrain requires, to replace the alternator by supplying power to the low voltage system (12 or 24 V) and to balance battery cells within the battery management system. A DC/DC converter with only one switch that step down the voltage is referred to as a “buck converter”. If the voltage is stepped up it is a “boost converter”. The combination is a “buck-boost converter” which can step the voltage either way. These three simple categories are all constructed with a single set of components, but differ in topology. DC/DC converters of higher order, i.e. with multiple switches, can be either isolated or non-isolated. Isolation means that the output is electrically separated from the input using a high-frequency transformer. This is common in step down DC/DC converters connecting the high voltage DC link to the 12 V system but also within battery management systems to balance voltage and charge between individual cells. Non-isolated versions are common for boosting the battery voltage to levels more suitable for the electric powertrain. For high power applications, above about 500 W, multi-switch bridge converters are appropriate. They build on the principles of the simpler types and are often referred to as “buck derived” or “boost derived” (Husain, 2011). Another term used coupled to DC/DC converters is “inverter driven”. This means that the first stage of the converter invert DC to AC. The voltage is then stepped up or down over the transformer and finally rectified back to DC. (Husain, 2011, Emadi, 2005).

**AC/DC on-board chargers** (OBCs) are rectifying converter units which enable charging of the traction battery from ordinary household sockets. A common topology is to use a power factor correction (PFC) rectifier followed by a full bridge isolated DC/DC converter stage (Gautam et al., 2011). The PFC stage includes another DC/DC boost circuit subsequent to the rectifying diode circuit. The boost circuit has the role to provide the power factor correction (Yun et al., 2011). This is necessary for OBCs in order to comply with the requirements of international standards and to reduce harmonics in the grid power system. The final DC/DC stage the converts the voltage to the desired level of the battery. OBCs range in capability from 1-7 kW (Botsford and Szczepanek, 2009) depending on the battery size and a typical value is 3.5 kW (Nemry and Brons, 2010).

### 3.2 Power semiconductor devices

Transistors are the main building blocks of all traction inverter units. A transistor is a type of active and controllable semiconductor device which can switch on and off at high frequency. Thus, they can be used as power switches and generate pulses with different widths. Working together, a set of switches can emulate sinusoidal AC waveforms from a DC voltage supply. This is referred to as pulse width modulation (PWM). AC type electrical machines, for example induction machines (IMs) and permanent magnet synchronous machines (PMSMs), are commonly controlled by three phase inverter units, based on a “bridge” shaped topology of six power switches mounted into a power module (Jahns and Blasko, 2001, Volke and Hornkamp, 2012, Husain, 2011, Hughes and Drury, 2013). A power diode is mounted in parallel with each transistor in the bridge, permitting current to flow in the reverse direction, passing by the switch, for example when energy flows from the electrical machine to the battery during regeneration of brake energy. The diode protects the transistor from high voltage transients coupled to the switching (Husain, 2011, Volke and Hornkamp, 2012). Contrary to transistors, diodes are passive and uncontrollable semiconductor devices. Figure 5 shows a schematic drawing of a typical transistor bridge for automotive applications.

Transistors have three terminals. Two are terminals for the switch itself and the third is used to control the switching. Nearly all power switches in low and medium power applications, such as automotive traction inverter units, are made metal oxide semiconductor field effect transistors (MOSFETs) or insulated gate bipolar transistors (IGBTs) (Emadi, 2005, Husain, 2011, Volke and Hornkamp, 2012). These types of transistors are voltage controlled and the third terminal is referred to as the “gate”. The control signal originates from a microcontroller, but the signal must be boosted both in voltage and current in a separate driver stage, see Section 3.3.

In terms of material, today’s power devices are primarily made of silicon that have been doped in segments with other elements, for example phosphorus or boron, to achieve the desired electronic properties (Volke and Hornkamp, 2012, Flack et al., 2016). New competing base materials are emerging (see Section 3.6), but silicon technology benefits from relatively simple processing, good resource availability and that material properties are well known and documented (Flack et al., 2016).
For IGBTs, maximum voltages can range up to 6500 V, and currents up to 1500 A (Infineon, 2016), and offered automotive classed components range up to 1200 V and 800 A (Infineon, 2014a). Compared to silicon MOSFETs, IGBTs have better current conduction capability, implying much smaller conduction losses in high-voltage applications. Hence, automotive traction inverter units with power ratings higher than 20 kW almost always use IGBTs (Emadi, 2005, Husain, 2011, Guerra, 2011, Volke and Hornkamp, 2012, Hughes and Drury, 2013, Krah et al., 2013, Albanna et al., 2016). For conventional PWM, IGBTs are limited to operation frequencies of 50 kHz or lower (Emadi, 2005), but this is not an issue since most automotive motor drive applications use much lower frequencies. IGBTs can also be found in converter types but the turn-off switching speed is slower than for MOSFETs and switching losses are higher at high frequency. Automotive IGBTs generally have thermal requirements for handling over 500 000 cycles over 40°C ambient temperature, and more than 1000 cycles for the extreme case of going from -40°C to 125°C (Jahns and Blasko, 2001). For voltage ratings below 200 V, MOSFETs are most common since they are then the most cost effective solution. They are also used for the 200-600 V range when high switching speed is required but with low power. Maximum current ratings span from a few hundred mA to a bit over 100 A (Emadi, 2005).

In connection to examples of rated values in the case of transistors, it is important to point out such values in manufacturers’ datasheets represent the boundary for the device to operate without self-damaging. This includes transient overvoltages and overcurrents, as well as high temperatures at the transistor junctions (Emadi, 2005). Overcurrent means that the current becomes too high when transistor is transmitting, and that it is destroyed by overheating. Overvoltage means that the voltage in off-mode becomes too high. The transistor breaks down and is set in on-mode permanently. Hence, safety margins are considered when devices are selected for circuit and component design. Normal operating conditions can be expected to be much lower than the rated maximum values. Typical DC supply voltage for powertrains in smaller road vehicles such as electric cars is in the range of 200-400 V.

3.3 The main building blocks of an inverter unit

An inverter contains several building blocks to become a fully functioning unit. Active semiconductor parts are referred to as chips. These are packaged in a module which must provide proper encapsulation, bond wires, conductors and connectors, as well as handle heat dissipation from each chip (Volke and Hornkamp, 2012). This package containing the transistor bridge which is manufactured and sold as a complete subpart is called the IGBT module or power module.

The DC side of the inverter coupled to the battery is conventionally referred to as the “DC link”\(^4\). The reason is that in most industrial applications is the inverter one stage within a motor controller which receive its input from the AC utility supply (Hughes and Drury, 2013). A rectifying stage then precedes the DC stage which becomes a link between the two converter stages (see Section 3.1 for an explanation of the converter terminology). Relatively large, bulky and expensive capacitors are required to stabilize the DC link by providing reactive power to overcome leakage inductance, reduce emission of electromagnetic interference and minimize effects of the switching operation (Grinberg and Palmer, 2005, Volke and Hornkamp, 2012, Wen et al., 2012). It is important to protect the battery from too large ripple currents and the switches from too

---

\(^4\) The terms “DC system” and “DC bus” are also used.
large voltage spikes. (Salcone and Bond, 2009, Wen et al., 2012). These capacitors are called DC link capacitors. Grouped together, the power module and the DC link capacitors are sometimes referred to as the power stage.

Additional capacitors are sometimes included to provide further protection against voltage spikes (Brubaker et al., 2012, Volke and Hornkamp, 2012), referred to as snubber capacitors. However, improvements in the switching control and careful design of the DC link structure can eliminate the need for such extra components (Brubaker et al., 2012, Volke and Hornkamp, 2012). Designs without snubber capacitors are sought and preferred to avoid the additional cost, weight, and volume, and decreased reliability and durability.

The inverter unit also includes one or more low voltage operated printed circuits boards\(^5\) (PCBs) including a driver stage to govern the switching of the power switches, sensors and microcontrollers for logic control, as well as diagnostic and protective devices. The main role of a driver board is to supply the IGBT module with suitable control voltage, more specifically a voltage to the gate of each IGBT (Volke and Hornkamp, 2012), using the vehicle power supply (12 or 24 V). The logic circuits on the driver board handle the switching signals, various fault signals and protection measures. The role of a logic board is to control the driver board (and consequently the complete unit) based on command inputs from the vehicle’s overall powertrain control algorithm, combined with feedback signals from various sensors on current, voltage, power module temperature and the position of the motor. This functionality is realized by mounting several blocks of standard electronic components onto the PCB(s), also including communication interfaces and filters. Figure 6 shows the topology of the unit, i.e. an overview of the electronic subparts and how they relate.

Furthermore, the different electronic subparts must be integrated both electrically and mechanically. A bus bar is a metallic bar or strip that conducts electricity between the subcomponent terminals within an electronic unit. For example, there are smaller bus bars included both in the power module and the DC link capacitor. However, the laminated bus bar is a larger subpart of its own, with layers of fabricated copper separated by

---

\(^5\) The term printed wiring board (PWB) is also commonly used.

---

Figure 6: Overview of an inverter unit (dotted box), including its main electronic subparts (dashed boxes) and how it couples to the battery and the electric motor, adapted from Husain (2011).
thin dielectric materials, which has been laminated into a unified structure (Mersen, 2013). It offers a complete power distribution subsystem within the unit between the power stage parts and to and from the connectors. It also acts a structural part along with the aluminum casing. The latter consist of a housing compartment and a heat sink, to contain and protect the electronic subparts and provide proper cooling of the power stage. The heatsink can be designed either for liquid cooling or air cooling. The housing compartment constitutes the frame for internal mounting of subparts and the aim is to achieve a high density internal packing. Similarly, the complete casing comprises the frame for mounting the unit itself with the aim to achieve a well-fitted installation together with other units of the powertrain. Hence, the shape of the housing compartment and the cooling arrangement is a delicate engineering balance which governs the overall electric and thermal performance of the unit, its volume and its ease of assembly. From an LCI point of view it is also noteworthy that the casing is the heaviest subpart, but its share of the total weight can vary greatly depending on design selections, making it very hard to capture in a generic model.

3.4 Power rating and the importance of cooling

Inverter unit specifications often present a voltage operating span (Bosch, 2008, Siemens, 2015, Brusa, 2013a, b, Siemens, 2014, Inmotion, 2016) along with the rated values for nominal and peak current (Bosch, 2008, Siemens, 2015, Brusa, 2013a, b, Siemens, 2014, Inmotion, 2016). In this case “nominal” refers to continuous operation. Sometimes there are also rated values for nominal and peak power presented (Brusa, 2013a, b, Siemens, 2014). However, power is generally not a design requirement in itself. Instead, current requirements are the starting point for power electronic engineering design work (Waern, 2012). In turn, the continuous power capability of the inverter unit is closely related to the cooling capacity of the design. Foremost, various rated maximum rated parameters for the semiconductor devices, the power module or the DC link capacitors must not be exceeded, to avoid immediate failure and breakdown coupled to overcurrents and overvoltages, as presented in Section 3.2. However, these subparts are usually selected with notable margins in relation to the intended working conditions. But, for continuous normal operation the unit must also have sufficient ability to dissipate heat losses, mainly from the power stage, e.g. to handle heat generated by conductance and switching losses in the power module. This section of the report provides a technical background and discussion about this relationship, i.e. how the inverter power capability relates to its cooling capacity, and related avoidance of performance degradation. The matching of requirements between the inverter unit and the electric motor is another topic discussed here, as a part of an explanation and motivation for important technical assumptions made in the LCI modeling work, related to power and cooling.

The requirements for cooling of the power module are a good starting point. Heat losses occur in other subparts of the inverter as well, mostly in the DC link capacitor, but the power module is the major contributor. The heat lost in the module is referred to as thermal power dissipation. In order for the module to operate properly, the following equation should be in balance:

\[ P_{\text{power module thermal dissipation}} = P_{\text{conduction losses}} + P_{\text{switching losses}} \]

Consequently, the highest tolerable current for a power module can only be specified in relation to the chip temperature and the cooling effect. As an example, for the baseline unit with 80 kW nominal power rating, the power module has been labelled to 800 A (Infineon, 2011). However, the maximum allowed temperature for the IGBT and diode chips is 175°C. The highest possible continuous DC-current becomes 700 A if the interface between the module and heatsink holds 25°C, and 550 A if it holds 75°C. On the other hand, the module can also safely withstand 1-millisecond pulses up to 1600 A if the DC link voltage is at most 450 V (Infineon, 2010a, 2011). A reasonable operation point for this module could be 220 A, 350 V, 10 kHz of switching frequency and 150°C of chip temperature. This set of parameters gives a power loss of about 1100 W for the voltage drop over the transistors and diodes, and the losses due to the switching, according to a calculation procedure for power losses provided by (Christmann et al., 2009), and the module output characteristics curves (Infineon, 2011). The maximum allowed power dissipation of the module has been specified to 1.5 kW when the cooling interface is operating at 25°C.

Furthermore, the voltage of the DC link upheld by the battery is dependent on the battery state-of-charge. The rated battery voltage refers to a fully charged battery pack. When state-of-charge goes down, so does the battery voltage. As a response, the current through the inverter unit increases in order to deliver sufficient
power to the electric motor. Hence, the highest tolerable currents will pass through the power module at a much lower battery voltage than the rated value. Conversely, in regenerative mode the battery voltage may go above the rated value for the battery for some time. But, the dimensioning of the inverter unit cooling system must be made for the case of high current and low voltage. For this reason there is a benefit from the converter point of view, if the system is designed with a high rated DC link voltage as it will decrease the thermal stress on the power module and enhance the life length of bond wires and solder layers (Christmann et al., 2009). This is also a part of the explanation to why applications demanding more power, such as heavy commercial vehicles, use higher battery voltage than passenger cars. Then again, in both cases it requires IGBT and diode chips which can handle higher voltages.

Furthermore, similar to electrical machines, inverters can also be temporarily overloaded and then return to steady-state operation without being damaged or degraded. This explains why there is a difference between nominal and peak values. Electric motors may be thermally dimensioned to the mean power losses during driving, which are much lower than the peak power losses. Short term accelerations then results in an increased temperature primarily in the windings of the motor, but other parts are not significantly affected. Heat is temporarily buffered, and dissipated later, when losses and power output is lower. The advantage is that the cooling arrangement can be simplified to handle only a fraction of the maximum power losses. The peak rating of an electric motor can therefore be 2-4 times that of its continuous rating (Grunditz and Thiringer, 2016). The same phenomena may also be utilized in inverter units, but for a shorter time and with a relatively smaller peak loads. All bulk material under the semiconductor chips then act as a thermal buffer to allow the current to be increased over a short time interval. Typically, an inverter unit is able to provide this peak power (maximum current) to the motor for 5-10 seconds when there is a need for a short acceleration, before it is constrained by too high temperature (Stervik, 2012, Waern, 2012).

For automotive electric traction motors it is common to specify the maximum power level. The reason is that dynamic characteristics, such as acceleration, is important. In other industries where applications are stationary and run at steady-state, ratings always consider continuous operation. The difference between continuous and maximum rating is important to keep in mind when comparing and interpreting component and powertrain specifications. City bus, distribution truck or passenger car operation often include many short accelerations making it possible, although not always desirable, to match the maximum capacity of the inverter unit with the peak power of the electric motor. Differently, long-haul trucks and coaches use the maximum motor power for much longer times, in slow accelerations and uphill driving, making it necessary to match the continuous rating of the inverter unit with the motor peak power.

Safety limits and prolonged life length are often prioritized in inverter design. Two examples of this are given by the 2010 version of the Toyota Prius (Burress et al., 2011) and the 2012 Nissan Leaf (Burress and Campbell, 2013). The 2010 Toyota Prius electric machine is rated to 60 kW peak power, and powertrain is able to deliver this power for 18 seconds before the motor is overheated (Burress et al., 2011). It can handle 50 kW for about four and half minute. In the Leaf both the inverter and the electric machine can operate continuously at 80 kW, which is the stated maximum power, and tests indicate that higher power levels are possible (Burress and Campbell, 2013, Miller, 2013b). However, the energy available in when the battery is fully charged is 24 kWh. Thus, it can support a little more than a quarter of an hour driving at this power, indicating that the system design of the powertrain is far from being optimized in terms of cost and efficiency. Effective and apt housing and cooling design is a very important explanation for the improvements achieved in power densities of motor controllers over the last few years (Burress et al., 2011, Kang, 2012). For example, the weights of the motor control inverter units are almost the same in the 2007 model of the Toyota Camry as in the 2008 Lexus LS600H, but the latter supports 40 kW more for motor peak power (Burress et al., 2009).The 2010 Toyota Prius motor control inverter accounts for about 3.6 kg of the PCU weight, more than 5 kg less than the same unit in the 2004 Toyota Prius, despite that the peak power of the motor is 10 kW higher (Burress et al., 2011).

To conclude, the fulfillment of the thermal requirements for the power stage is a key to a fully functioning inverter unit. Additionally, the rated values for the inverter cannot be expected to perfectly match the electrical machine rating. However, if no specific information is available it is reasonable to assume that the rated nominal value of the inverter, i.e. for continuous operation, should be matching the peak rating of the electric machine. This is in line with observations made in benchmarking literature for the matching of the electric motor and the motor controller in terms of capability (Burress et al., 2011, Burress and Campbell, 2013, Sarlioglu et al., 2015).
3.5 Integrated packaging and variability in design

There are many options for the design of power electronic converters in vehicles. Different engineering selections can fulfill similar requirements, for example in the circuit design of the power stage and even more so for the controlling low voltage PCBs. Foremost, the selection of cooling system and integration of the casing with other parts is the largest source of design variability, especially related to packaging (Burress and Campbell, 2013). For the cooling, there is a large difference if the heatsink is cooled using a liquid or with air (Volke and Hornkamp, 2012). Liquid cooling is more efficient but it requires a coolant circuit with hoses and a pump. The casing must have sufficient bulk to allow for channels and cavities. Air cooling on the other hand, is often accomplished using fins which mainly dismiss energy through convection. Simple ventilation requires a large heatsink whereas forced convection using a fan makes it possible to reduce the fin size considerably.

Furthermore, especially in passenger cars it is common that more than one power electronic unit, e.g. the inverter and different types of DC/DC converters, are integrated within the same casing and share several subcomponents, such as DC link capacitors and bus bars for current conduction (Burress and Campbell, 2013). As an example, the 2010 version of the Toyota Prius’ power control unit (PCU) gathers two separate inverters, one for motor control and one for generator control, one boost DC/DC converter and one step-down DC/DC converter in the same liquid cooled casing (Burress et al., 2011). The two inverters and the larger boost DC/DC converter share power supply and driver electronics are grouped together onto two common printed circuit boards (PCBs) (Burress et al., 2011). The 2008 Lexus LS 600H has a similar, but larger, integrated PCU (Burress et al., 2009). In general, this allots a smaller share of the housing compartment and the heatsink to each integrated power electronic unit compared to a stand-alone unit. A linked trend is that the electric machine and power converters are further integrated and packaged together (Shimizu et al., 2013). An important driving force is to reduce electromagnetic interference due to interconnecting power but also potential cost reduction (Jahns and Blasko, 2001).

In contrast to the trend of change in packaging of inverter units, power modules are generally designed according to a standard concept which is dominating in the medium power range and for automotive applications (Volke and Hornkamp, 2012), see Section 4.1.2. This standard design has been more or less the same for the last 25 years (Tan et al., 2010, Volke and Hornkamp, 2012), despite that development has provided a great variety of solutions for other parts of the power range. An important explanation is the requirements for robustness and durability on the module, for example life times of above 20 years in related railway applications.

DC link capacitors have traditionally been of electrolytic type, mainly owing to competitive cost. However, due to the progress in plastic film capacitor technology during the last decade, this type of capacitors is replacing the electrolytic version in most DC link applications and has been established as the primary selection for automotive electric drive systems (Grinberg and Palmer, 2005, Salcone and Bond, 2009, Wen et al., 2012, AVX, 2015) It has enabled a reduction for the amount of capacitance necessary on the DC link, as well as improved power density, lower losses and longer lifetime (Wen et al., 2012).

As a summary, inverter topology offer design variability which mainly relates to packaging and cooling. Most importantly, from an LCI point of view, it implies that the load of the casing can be shared with units providing other functionality. On the other hand, as regards the inverter power stage, it is possible to identify a typical design setup for most automotive applications: an IGBT bridge based power module combined with a plastic film DC link capacitor.

3.6 Other transistor types and new materials

Until the 1980’s, heavy DC series motors were very often used in EVs, partly due excellent characteristics, but also due to their ease of control (Husain, 2011). AC/DC rectifiers was then the most mature converter technology (Jahns and Blasko, 2001). However, at this time new types of power semiconductors enabled AC machine control with inverter technology. The first step was thyristors (SCR, silicon controlled rectifiers) used in current-source inverters. Eventually it was followed by a series of semiconductors which could be turned off at the gate/base terminal such as gate turn-off thyristors (GTOs), bipolar junction transistors (BJTs), MOSFETs and IGBTs. The first two are controlled by varying the current amplitude and the latter two are controlled by regulating the voltage.

Today, IGBT technology is dominating for automotive power applications (Emadi, 2005, Husain, 2011, Guerra, 2011, Volke and Hornkamp, 2012, Hughes and Drury, 2013, Krah et al., 2013, Albanna et al., 2016), but MOSFETs are subject to the most intense progress in terms of power module design (Guerra, 2011, Davis,
As the theoretical limit of silicon based devices has been approaching, focus has also turned to wide bandgap (WBG) materials, mainly silicon carbide (SiC) and gallium nitride (GaN) (Emadi, 2005, Guerra, 2011, Albanna et al., 2016). Devices based on these new materials have lower losses and are capable of handling higher temperatures and switching frequencies. Over time, progress in loss reduction has made it possible to remove passive subcomponents such as transformers and filters containing inductors and capacitors from power electronic units (Jahns and Blasko, 2001). The development of WBG materials now implies that the structure of the whole power module can be refined and condensed as it requires less cooling (Davis, 2009, Krah et al., 2013). SiC devices are already commercially available, but especially SiC transistors are still costly and have been struggling with performance issues deriving from defects caused during fabrication (Volke and Hornkamp, 2012, Albanna et al., 2016). The potential of GaN devices is even greater, but the research frontier is roughly 10 years behind that of SiC (Davis, 2009, Volke and Hornkamp, 2012). However, during the time SiC devices have emerged, silicon based IGBTs have continued to develop to become an enabling technology for electrification of vehicles, largely based on improvements in production leading to decreasing component cost and high reliability (Guerra, 2011, Sarlioglu et al., 2015).
4 Design and representation of the inverter unit

4.1 Electronic subparts

4.1.1 Baseline data and general arrangement of reference units

The description of inverter technology in Chapter 3 reveals that generic characteristics can be identified for automotive units acting in electric motor drives. Such a setup includes a power module with a full bridge of silicon IGBTs (Emadi, 2005, Husain, 2011, Guerra, 2011, Volke and Hornkamp, 2012, Hughes and Drury, 2013, Krah et al., 2013, Albanna et al., 2016). Power MOSFETs and other chip materials are under development, but doped silicon IGBTs are still dominating for automotive applications. Delving deeper into details, IGBT chips can be differenti- ated based on their structure. Several improvements in chip technology over the last 20 years have reduced losses and silicon use, and increased power density (Volke and Hornkamp, 2012). “Trench field stop” structures are now common and fabricated in high volumes (Guerra, 2011).

The power stage typically contain one large or a few plastic film DC link capacitors (Grinberg and Palmer, 2005, Salcone and Bond, 2009, Wen et al., 2012, AVX, 2015), whereas snubber capacitors are excluded by means of careful design and proper switching control (Brubaker et al., 2012, Volke and Hornkamp, 2012). Furthermore, there is a need for low voltage PCBs with gate drivers and logic circuits providing functionality such as sensor signal handling, communication interfaces and filters. In summary, a typical three phase inverter unit contains all main building blocks presented in Section 3.3, arranged in a topology as shown in Figure 6.

In addition, full inverter functionality requires internal circuit conductors, proper cooling and a protective casing, which is further discussed in detail in Section 4.2. Especially, the thermal requirements for the power stage are very important for the power capacity of the unit. In Section 3.4 it is established, as a rule of thumb for a generic design, that the rated value for continuous operation of the inverter should match the peak power rating of the electrical machine, (Burress et al., 2011, Burress and Campbell, 2013, Sarlioglu et al., 2015).

Data collection

Data for the general arrangement of two inverter units was gathered from Infineon (2012a, 2014b), and was found to be well in line with the generic characteristics discussed above, as well as the topology shown in Figure 6. The Hybrid Kit for HybridPACK™1 is made up of two PCBs, one driver board and one logic board, one IGBT Module HybridPACK™1, a recommended DC link capacitor and suggested cooler proposal. All subparts are mechanically and electrically suitable to be used in conjunction and together they constitute complete main inverter unit for electric drive applications, rated to 20 kW nominally (Infineon, 2012a, b). The Hybrid Kit for HybridPACK™2 has an identical arrangement as the Hybrid Kit for HybridPACK™1, with subparts that are mechanically and electrically matched. Together they constitute a complete main inverter unit for electric drive applications, rated to 80 kW nominally (Infineon, 2012c, 2014b). Hence, these two Infineon inverter units were selected as the baseline data to create two associated “reference units” for the scalable inverter design, and used to link the subcomponent’s size in mass and geometry to the requirements for peak power of a coupled electric motor, at 20 kW and 80 kW respectively. The difference between the existing “baseline units” and the constructed “reference units”, are that the former have no design specified for the casing with connectors and different cooling options, or for the laminated bus bar; each unit has two recommended versions for the DC link capacitors; and there are some differences regarding materials in conductors and conducting surface layers inside the power module; whereas the latter were adapted to become uniform reference points for all materials and subparts in the mathematical scaling operation.

The active IGBT chips of the two baseline inverters are of the trench field stop type (Infineon, 2012a, 2014b). Moreover, the specifications of the recommended DC link capacitors states that the rated battery voltage is expected to be 450 V for both inverter units (Infineon, 2012a, 2014b). This value was taken as a starting point the scaling of the DC link capacitor, not only accounting for power requirements of the inverter unit, but also the rated battery voltage. Overall, the established reference data was found valid for modeling and rescaling the inverter unit for a power span of 20-200 kW and a voltage span of 250-700 V.

4.1.2 Power module design and principle for scaling

The active semiconductor devices are the key to the design of the power module. Still, their contribution to the total mass of the module is small. Other subparts account for 99.8% of the weight. The material selection is governed by both electrical and thermal properties. The structure of design is shown in Figure 7.
Starting with the semiconductor chips, these are soldered onto copper tracks which form a pattern of conductors on a ceramic substrate. Bond wires connect the conductors in the pattern with the external terminals of power module, as well as between tracks and the upper terminals of the chips. The ceramic substrate is very thin – 250 µm to 1 mm thick (KCC, 2012) – and acts as an electric insulator with high thermal conductivity. It is typically made of aluminum oxide, also referred to as “alumina”, or aluminum nitride (KCC, 2012, Volke and Hornkamp, 2012). The conductors are directly bonded to the substrate surface. Underneath there is another foil of pure copper, also directly bonded to the substrate’s opposite side. This design, with one ceramic substrate in the middle and two copper layers on each side is often referred to as a DCB (direct copper bonded substrate) (Volke and Hornkamp, 2012). The foil on the underside allows soldering to a copper baseplate with the role to transfer heat over to the cooling medium. Nearly all modules in the medium power range have a baseplate, which usually is 3-8 mm thick (Volke and Hornkamp, 2012).

Bond wires are made of aluminum or copper. The latter enable higher power density (Volke and Hornkamp, 2012, Sheng and Colino, 2005). In order to be RoHS\(^6\) compliant, the solder must be lead-free, commonly as a mixture of tin and 3-4% of silver (Sheng and Colino, 2005). There may also be a small amount of copper present in the solder mix. External terminals and contacts are often made of different copper- or nickel-alloys or brass (Sheng and Colino, 2005), or pure copper if the current requirements are higher (Volke and Hornkamp, 2012). However, the main power terminals (not explicitly shown in Figure 7), are often made for screw connection (Volke and Hornkamp, 2012). Screws offer robust mounting of the module and a relatively large contact area directly to the DCB or to copper contacts connected to the DCB, i.e. low contact resistance. Several different metals are possible, e.g. galvanized low alloy steel.

Frames and lids are generally made in plastics with high mechanical and thermal stability, and good electrical insulation. Such rigorous requirements are met by some polymers: polyphenylene sulfide (PPS) and polybutylene terephthalate (PBT) (Volke and Hornkamp, 2012). The plastic frame is also anchor contacts and terminals. As a consequence, the polymer must be mixed with a filler material, for example glass fiber, to adopt its thermal expansion coefficient with that of the terminals (Sheng and Colino, 2005). Moreover, flame proofing substances are sometimes added as a small constituent of the casing, for example diantimony trioxide, despite that this substance is subject to regulation (Infineon, 2009, 2014c, Volke and Hornkamp, 2012).

Finally, there is an insulating potting compound, encapsulating the other components within the frame. Silicone\(^7\) gel is a typical choice, as it is flexible over a large temperature range, have high purity, high chemical resistance and low toxicity (Sheng and Colino, 2005, Volke and Hornkamp, 2012). It acts as a contamination barrier for the active and conducting parts of the modules. However, the silicone gel may absorb moisture from air, including any sulfur-containing substances, so the copper surfaces of the DCB and the copper auxiliary terminals have to be coated, often nickel-plated, to avoid contamination and risk for short circuit failure (Volke and Hornkamp, 2012). The copper baseplate is also nickel-plated in a 3-10 µm layer. Epoxy resins are sometimes used as an overcoat encapsulation, on top of the silicone gel (Sheng and Colino, 2005, Volke and Hornkamp, 2012). In such cases, the potting compound also becomes a mechanical support, together with the frame. However, the use of an extra epoxy layer is now less common (Volke and Hornkamp, 2012).

\(^6\) RoHS – Restriction of the use of certain Hazardous Substances in Electric and Electronic Equipment. The second version of this EU directive (2011/65/EU) became effective January 2:nd 2013 (Kemikalieinspektionen, 2016).

\(^7\) Silicone is a polymer material, with different properties than, but also containing, the elementary substance silicon.
Data collection

The data for the material composition of the power module in LCI model was collected from Infineon Technologies AG, for two IGBT power modules. This baseline data was used to establish two reference modules, as presented in Section 4.1.1 in line with approach for the complete reference inverter units. The material content data sheet for the IGBT Module HybridPACK™1 (Infineon, 2008), provided the input to establish the smaller reference unit, at 20 kW. Hereafter in this section of the text, this power module is referred to as the “small reference module”. Similarly, the material content data sheet for the IGBT Module HybridPACK™2 (Infineon, 2009) was used for the 80 kW reference inverter unit. This module is referred to as the “large reference module”. Both baseline units was documented for production year 2009, but declared by Infineon to remain as valid also in June 2014 (Heinicke, 2014).

However, there are design differences between the two baseline power modules. Hence, in order to enable usage of the data for scaling between different sizes of the inverter unit depending on the power and voltage requirements, the reference data had to be aligned in terms of design selections, i.e. to establish the reference units from the baseline data units. Proper scaling also required that some material constituents were grouped together and identified as compound materials or coatings on other base materials in the subparts of each module. As a consequence, the original baseline data for the modules was slightly reworked, in accordance with the following description.

First, the material content data sheets for the two baseline units showed that the small module have contacts and auxiliary terminals made of brass and aluminum bond wires, whereas the large module mostly have pure copper in conductors and pin contacts, and only a very small fraction of aluminum (Infineon, 2008, 2009). In order to harmonize these material selections, it was assumed that pure copper is used in auxiliary terminals, contact strips and bond wires, for the entire operating range. Brass used in power modules typically consist of 60-70% copper and 30-40% zinc (Sheng and Colino, 2005). Zinc has lower density than copper (Nordling and Österman, 1996). As a result, if these parts are unchanged in size, the weight reported as zinc increase with 26% when substituted to copper. Aluminum has even lower density. Shifting to copper wires with equal volume implies a weight difference by a factor of 3.3. However, copper has better conductivity and wires are likely selected to have the same electrical conductance rather than size. Hence, assuming pure metals and disregarding a minor alteration in the cooling effect of a smaller wire surface, bond wires become about a factor of 2.1 heavier when remodeled from aluminum to copper with equal conductivity and length8, using resistivity and density data from Nordling and Österman (1996).

The recalculation of brass and aluminum to copper also provided a starting point for assumptions about the weight shares of different copper subparts, and the amounts going into different manufacturing routes, described in Section 5.2.1. By geometric approximation, 5% of the copper mass was allocated to wires and 15% to terminals and contacts (leading to the terminals). The amount of foil integrated in the DCBs was linked to the alumina mass and area (see Section 5.5.3). Hence, the remaining and largest share resides in the baseplate. Appropriately, this mass share corresponds to a 3 mm thick baseplate for a 20 kW module, and increasingly thicker with a few millimeters over the whole model span up to 200 kW.

The thermoplastic frame material in the original baseline datasets was PBT, mixed with glass fiber and diantimony trioxide. However, PBT was not available in Ecoinvent 3 (Weidema et al., 2013) for the link to upstream data. Instead, the frame material was modeled as PPS as it is an equally common selection. Next, the weight relation between tin and silver for both module datasets stipulated a lead-free solder consisting of 95.5% tin and 3.8% silver. This is a common composition of lead-free solder, where the remaining 0.7% comes from copper (Sheng and Colino, 2005). The closest corresponding dataset found in Ecoinvent 3 (and used for the linked flow recommendation) contains the same amount of tin, but 3.9% silver and 0.6% copper.

Both baseline modules contain silicone gel as the encapsulant. They also have zinc, gold, oxydic glass and silicone adhesive as trace substances, i.e. in amounts less than 0.1% of the total weight. Although the mass is negligible, such substances may still be important if they imply demanding manufacturing processes or if the substance is hazardous. The zinc content was found to derive from galvanization. Steel is not only used in the main terminals, but also in small flat countersunk screws screwed from beneath, securing the baseplate to the frame. Based on the amount of steel present in the large module (Infineon, 2009), and the defined size of the module-screw threads (Infineon, 2010c), it was estimated that a 15 µm zinc coat layer would yield a material content of about 0.05%/in the reference units. This thickness is common for threaded metal goods (Walraven, 2011). The steel itself was assessed as a low-alloy type in the match with Ecoinvent 3 data.

Adhesive is used in a very thin layer when attaching the plastic frame to the baseplate and the lid onto the

---

8 It was derived that when setting the resistance and length equal for two conduction wires of different materials, the mass relationship can be found as the product of the resistivity quotient and density quotient, for the two materials.
frame (Sheng and Colino, 2005). It was estimated to correspond to 0.02% of the mass content in the reference units, based on module area and frame thickness. Gold is used as an additional plating over nickel on the auxiliary terminals (Infineon, 2010c), and it is also declared as a substance of concern by Infineon (2014c). Hence, it was included with an assumed mass portion of 0.01%. However, the oxydic glass present in the alumina ceramic is not declared to be of concern (Infineon, 2014c), and the traces amounts have not been found to have a role of its own in the design. Instead, the oxydic glass content is a matter of alumina purity (Classen et al., 2009). Oxydic glass was neglected in the material configuration of the reference units.

The total mass for the small and large baseline modules were specified to be 460–485 grams (Infineon, 2008) and 1.2–1.26 kg, respectively. After the harmonization of the design selections and the grouping of materials, and starting from the high end values of the original data, the final total mass for the 20 kW reference module was calculated to be 500 grams. The mass of the 80 kW module was set to 1.26 kg for the LCI model.

Finally, also after harmonization of data and the construction of the two reference units (based on the baseline modules), there are still differences in the proportions of different subparts. For example, the share of

![Figure 8: Linear scaling of the amount of copper in the power module in relation to the requirement for nominal inverter power.](image)

![Figure 9: Linear scaling per substance for PPS plastics, silicone gel, lead-free solder, steel and DCB alumina ceramics in the power module, in relation to the requirement for nominal inverter power.](image)
the packaging materials, i.e. the encapsulant, frame and lid, represent a larger share of the total mass in the smaller unit, indicating that the power density increase with power. In order to take this into the inventory model, the scaling between was implemented per substance assuming a linear relationship between the two reference datasets, i.e. one starting mass configuration was established for the modified dataset for a 20 kW power module (nominal rating, see Section 3.4) and a scale factor for each constituent over the complete power range, up to 200 kW. This resulted in the following calculation formula:

\[
\text{Mass}_{\text{module}} = \sum_{\text{All substances}} \left( \text{Mass}_{\text{substance @ 20 kW}} + \text{Scale factor}_{\text{substance}} \times (\text{Power}_{\text{User input}} - 20) \right)
\]  

(Eq. 1)

The data established for the model calculations of the power module is presented in Table 1. The resulting linear scaling per substance are illustrated in figures 8-10.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Mass, 20 kW unit</th>
<th>Scale factor</th>
<th>Power module part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium oxide</td>
<td>6.3 g</td>
<td>130 mg/kW</td>
<td>Ceramic substrate in DCB</td>
</tr>
<tr>
<td>Copper</td>
<td>344 g</td>
<td>10.5 g/kW</td>
<td>Baseplate, DCB foils, bond wires and terminals</td>
</tr>
<tr>
<td>Doped silicon</td>
<td>970 mg</td>
<td>5 mg/kW</td>
<td>Active semiconductor chips</td>
</tr>
<tr>
<td>Gold (coating)</td>
<td>49 mg</td>
<td>1.3 mg/kW</td>
<td>Auxiliary terminal coating</td>
</tr>
<tr>
<td>Nickel (coating)</td>
<td>680 mg</td>
<td>16 mg/kW</td>
<td>Coating on baseplate, DCB and terminals</td>
</tr>
<tr>
<td>Solder (95.5Sn/3.8Ag/0.7Cu)</td>
<td>12.7 g</td>
<td>360 mg/kW</td>
<td>Lead-free solder for bonding of parts</td>
</tr>
<tr>
<td>Steel</td>
<td>8.2 g</td>
<td>330 mg/kW</td>
<td>Galvanized steel parts</td>
</tr>
<tr>
<td>Zinc (coating)</td>
<td>250 mg</td>
<td>6.3 mg/kW</td>
<td>Plastic case and lid</td>
</tr>
<tr>
<td>Diantimony trioxide</td>
<td>3.7 g</td>
<td>22 mg/kW</td>
<td></td>
</tr>
<tr>
<td>Glass fiber</td>
<td>28 g</td>
<td>0.2 g/kW</td>
<td></td>
</tr>
<tr>
<td>Polypheylene sulfide (PPS)</td>
<td>62 g</td>
<td>0.5 g/kW</td>
<td></td>
</tr>
<tr>
<td>Silicone gel</td>
<td>33.5 g</td>
<td>640 mg/kW</td>
<td>Encapsulating potting compound</td>
</tr>
<tr>
<td>Silicone adhesive</td>
<td>97 mg</td>
<td>3 mg/kW</td>
<td>Bonding of case to baseplate and lid to case</td>
</tr>
</tbody>
</table>

Table 1: Scalable material composition of the power module, established for the LCI model based on the small and large reference units, in turn reworked from corresponding baseline data (Infineon, 2008, 2009).

Figure 10: Linear scaling per substance for nickel, gold and zinc coating, and doped silicon chips in the power module, in relation to the requirement for nominal inverter power.
4.1.3 DC link capacitor design and principle for scaling

The size of the DC link capacitor depends on the amount of energy it must absorb to attenuate the ripple currents caused by the switching operation and the amount of current it can handle in terms of heat from ohmic resistance (Cornell Dubilier, 2016). A capacitor is a device that can store electrical charge, measured as capacitance. This ability depends both on the properties of the dielectric material it is made of, and on the size and geometry of the capacitor. Additional typical design features, and guiding parameters when selecting a capacitor, are the allowable peak and ripple currents, and the maximum rated voltage pulse slope.

In present day inverter units DC link capacitors are commonly either aluminum electrolytic capacitors or plastic power film capacitors (Salcone and Bond, 2009, Wen et al., 2012, AVX, 2015). Historically, aluminum electrolytic capacitors was the preferred choice as they offer low cost per farad (Salcone and Bond, 2009), and have greater capacitance per unit volume and higher energy density compared to film capacitors (Cornell Dubilier, 2016). However, while the aluminum electrolytic technology at large has been unrefomed (Salcone and Bond, 2009), film type technology has continued to evolve and can today withstand much higher ripple currents and higher voltages. Also, modern film capacitors have become thermally and mechanically robust, and gained increased life-length (Salcone and Bond, 2009, AVX, 2015, Cornell Dubilier, 2016). Electrolytic capacitors have low ripple current capability, due to high resistance and inductance, and they suffer from degradation caused by self-heating (Salcone and Bond, 2009, Wen et al., 2012, Cornell Dubilier, 2016). As a consequence, this capacitor type is commonly oversized in terms of farads compared to film type capacitors (Salcone and Bond, 2009, Wen et al., 2012, AVX, 2015, Cornell Dubilier, 2016). Hence, despite its higher energy density, the capacitor becomes larger, heavier and more difficult to mount. Unsurprisingly, the trend is that plastic film technology is replacing aluminum electrolytic in most DC link applications (Grinberg and Palmer, 2005, Montanari et al., 2008, Brubaker et al., 2012).

Plastic film capacitors are often designed as wound or stacked layers of plastic film and metal in between (Vishay, 2012, Epcos, 2013, Cornell Dubilier, 2016). The plastic film acts as the dielectric medium and the metal as the electrode. “Thin films” have a thickness of less than 3.5 µm. The electrode can be either a metal foil or a metal layer deposited directly on the film, referred to as a “metallized film” (Cornell Dubilier, 2016). Typically, aluminum or zinc, or an alloy of the two, is used for metallization (Stahler, 2013, Cornell Dubilier, 2016). The metallization type has the benefit of self-healing, i.e. the electrode vaporizes in a small area around a fault, leading only to a minor loss of capacitance instead of complete capacitor failure. In the foiled version, aluminum or tin are the main constituents (Stahler, 2013). The advantage of this type is that it can handle higher currents because resistance and losses are lower (Stahler, 2013). The two types of electrodes can also be mixed into a hybrid version, resulting in a self-healing capacitor which still can withstand high currents (Cornell Dubilier, 2016). For automotive inverter applications, it is common to pack metallized films, or films with hybrid electrodes, into brick shaped casings and optimize for high density packing in the unit (Montanari et al., 2008, AVX, 2015).

Next, shifting focus from the type of DC link capacitor, to its size, it was observed that they grow in volume, mass and capacitance between inverter units with increasing power demand. However, this change in size does not only correlate with increasing requirements for power, but also with the DC system voltage rating. In a specific design situation, the sizing of the DC link capacitor involves many parameters. The capacitor must sufficiently attenuate both ripple current and ripple voltage to protect the transistor bridge and the battery at the same time as the capacitor itself must substisit hot spot temperatures and the ripple current, for all operating conditions (Wen et al., 2012). Ripple current handling is therefore one of the main considerations in selecting the DC link capacitor size (Salcone and Bond, 2009, Wen et al., 2012). Grinberg and Palmer (2005) argues that this is the primary factor to consider for film capacitors in battery-fed inverters, especially at high ambient temperatures. Compared to electrolytic capacitors, film capacitors enable significant reduction of the DC link size, and an improved bus bar design, in turn leading to a reduction of ripple voltage (Grinberg and Palmer, 2005).

Accordingly, ripple current was taken as the starting point in a simplified approach to establish a scaling equation. It was assumed that the capacitance C is selected to satisfy a maximum capability for ripple current handling \( I_{\text{RMS}} \), and that the two terms relate linearly as a first order approximation. In this equation, and all through to Eq. 6, letters are used to differentiate between different constants.

\[
C = \text{constant}_a \times I_{\text{RMS}} \quad \text{(Eq. 2)}
\]
Next, the ripple current that flows into the capacitor is proportional to the rated current $I_{DC}$ of the DC link, which in turn can be expressed in terms of the DC link power $P_{DC}$ and the capacitor nominal voltage $U$, such that the expression can be rewritten to:

$$C = \text{constant}_B \times I_{DC} = \text{constant}_B \times \frac{P_{DC}}{U} \quad (\text{Eq. 3})$$

Taking a different starting point, it can be noted that the internal structure of stacked and brick shaped capacitors allows the capacitance $C$ to be described by the equation for linear capacitors (Kaiser, 1993):

$$C = \text{constant}_{\text{dielectric}} \times \frac{A}{d} \quad (\text{Eq. 4})$$

where $A$ is the electrode surface area, $d$ is the thickness of the dielectric film and the dielectric constant is a material parameter. For a specific dielectric film, i.e., both in terms of the thickness and material, and an explicit internal winding structure of the capacitor, the capacitance grows with the electrode surface area. However, in such a case, both volume and mass also grows with the surface area. For example, for two brick shaped capacitors with the same arrangement in width, height and dielectric thickness, it is the linear difference in length which alters the capacitance as well as the mass, i.e. Eq. 4 can be rewritten to:

$$\text{Mass} = \text{constant}_C \times C \quad (\text{Eq. 5})$$

Merging and rearranging Eq. 3 and 5 gives

$$\text{Mass} = \text{constant}_D \times \frac{P_{DC}}{U} \quad (\text{Eq. 6})$$

Finally, the expression for the scaling of the DC link capacitor mass was established by restating $P_{DC}$ to the correlated nominally rated output power of the inverter, $P_{\text{inverter}}$, and expecting that the nominal rated voltage of the capacitor is selected to match the nominal rated voltage of the battery, $U_{\text{battery}}$:

$$\text{Mass}_{\text{capacitor}} = \text{Scale factor}_{\text{capacitor}} \times \frac{P_{\text{inverter}}}{U_{\text{battery}}} \quad (\text{Eq. 7})$$

**Data collection to establish the mass scale factor**

The DC link capacitor of the scalable inverter unit has been modeled based on data for brick shaped metallized plastic film capacitors for automotive inverter applications. This is line with the specifications provided by the two baseline units (Infineon, 2012a, 2014b), as well as technical description of the DC link capacitors, above. Furthermore, scaling was implemented based Eq. 7, for the total mass only, with one fixed material configuration for the entire operating span, in accordance with the discussion in the previous section.

The specification of the 80 kW baseline inverter unit became the starting point for the data collection to establish a mass scale factor for the capacitor. It recommends two brick shaped film capacitors that can be used in combination with the 80 kW power module, providing 500 µF at 450 V (Infineon, 2014b). The two units are manufactured by Epcos AG (B2565J4507K type) and Kemet Electronics (C4EEGMX6500AAUK type). Both capacitors have very similar electrical and thermal specifications, identical size and an average weight of 1.2 kg (Infineon, 2014b).

However, capacitors with comparable electrical properties do not always have identical mechanical and thermal properties. Also, the design may exceed the requirements in some aspects in order to be well functioning as regards other requirements. For example, the specification for the smaller 20 kW baseline inverter unit (Infineon, 2012a), recommends capacitors with notable difference in size to accomplish the same DC link capacitance for the same voltage rating, 300 µF and 450 V. The first, from Epcos AG has a volume...
of 0.5 dm³ and weighs⁹ 0.7 kg (Epcos, 2011a), and the other one, from Kemet Electronics occupies less half the volume (0.23 dm³) and has a weight of 0.35 kg (Infineon, 2012a). One explanation for this difference is that the smaller of the two has been designed for use in combination with active cooling (Infineon, 2012a). Another example was found in the same B25655-series of power film capacitors from Epcos AG, for two capacitors specifically designed for use with IGBT power modules (M651/M652 type) from Fuji Electric (Epcos, 2014a, b). Here, the same capacitor case volume and mass of 0.8 kg accomplish different capacitance suitable for inverter units of 20 kW as well as 50 kW (Epcos, 2014a, b, Fuji Electric, 2016).

The relationship between capacitor size and mass, and different electric, thermal and mechanical requirements is a complex issue. However, both thermal and mechanical requirements on the capacitor are coupled to the design and heat dissipation ability of the surrounding case. In an inverter unit design aimed for high volume production, it is likely that casing and capacitor requirements are balanced and optimized together. Based on this reasoning, it was found reasonable that the 300 µF capacitors from Epcos (2011a, 2014a) could be regarded as oversized for installation in 20 kW inverter units and therefore less representative for the LCI model data collection. Hence, they were left out when the mass scale factor was calculated. In summary, mass data was compiled for four brick shaped automotive power film capacitors where data for mass, nominal power of the complete inverter unit and the rated battery voltage was available for the same component. Since they all were rated for 450 V, Table 2 was established to compare the mass to power ratio for each capacitor.

Next, an average value was calculated for the mass to power ratio multiplied with the rated battery voltage of 450 V, to find a mass scale factor which could be used in Eq. 7.

\[
\text{Scale factor}_{\text{capacitor}} = 7.14 \text{ kg·V/kW}
\]

Resulting estimations for the DC link capacitor mass over the complete model voltage span, 250-700 V, for some selected power values are shown in Figure 11.

Finally, it was noted that the amount of copper in the terminals of the capacitors, increase in steps. The number of terminals starts from two or four and grows to more terminals with increasing capacitor size. However, the dimensions of each terminal may also vary. Hence, for simplicity, the terminals have been included in the total mass scaling as any other part according to Eq. 7, using the established scale factor.

**Data collection to establish the mass composition**

New material composition data was gathered for an automotive hybrid power film capacitor, as reference data for the composition of the DC link capacitor in the model. Data was collected from Epcos (2011b), corresponding to one of the recommended DC link capacitors for the 80 kW baseline inverter unit (Infineon, 2014b). In line with the technical background of this section, it was collected as one fixed configuration, separated from the mass scaling. This procedure was found rational as it was noted that all capacitors discussed in the mass scale factor data collection description above, had similar proportions between their total mass and the case volume, about 1.4-1.5 grams per cm³ (Epcos, 2011a, 2014a, b, Infineon, 2012a, 2014b). The mass composition of the DC link capacitor is presented in Table 3.

---

⁹ The baseline inverter unit specification and the manufacturer’s material content datasheet specify weights that differ with 50 grams. The value provided directly from Epcos AG is referred to here.
25

Figure 11: Estimated DC link capacitor mass over the complete model voltage span, 250-700 V, for some selected inverter unit power rating values, based on the established mass scaling model.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Mass share</th>
<th>Capacitor part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.1%</td>
<td>Electrode material</td>
</tr>
<tr>
<td>Copper</td>
<td>0.1%</td>
<td>Electrode material</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>29.2%</td>
<td>Dielectric</td>
</tr>
<tr>
<td>Tin</td>
<td>3.1%</td>
<td>Electrode material</td>
</tr>
<tr>
<td>Zinc</td>
<td>7.1%</td>
<td>Electrode material</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>19.0%</td>
<td>Plastic frame</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td>0.9%</td>
<td>Plastic frame</td>
</tr>
<tr>
<td>Polyurethane resin</td>
<td>14.4%</td>
<td>Encapsulation compound</td>
</tr>
<tr>
<td>Brass (64% copper, 36% zinc)</td>
<td>0.4%</td>
<td>Terminal coating</td>
</tr>
<tr>
<td>Copper</td>
<td>25.1%</td>
<td>Internal bus-bars and terminals</td>
</tr>
<tr>
<td>Tin</td>
<td>0.6%</td>
<td>Terminal coating</td>
</tr>
</tbody>
</table>

Table 3: Fixed material composition of the DC link capacitor, used in the LCI model based on original data from Epcos (2011b).

4.1.4 Driver board

The driver board controls the switching of the transistor bridge in the power module by regulating the voltage and providing a suitable current to the gate of each IGBT. In essence, the gate driver amplifies the control signals from logic circuits of the inverter unit to the gate input requirements of the power module (Volke and Hornkamp, 2012). For a bridge with six switches, the driver board must have six channels of driver circuits, in themselves containing transistors, capacitors and other electronic devices. The input logic control signals and the output IGBT gate control signals must have galvanic separation (Volke and Hornkamp, 2012). This can be achieved using optocouplers, a device which combines light emitting and light sensing subparts to transfer the signal using light. Moreover, each gate driver must be fed with a supply voltage, also requiring isolation (Fuji Electric, 2015). Hence, an isolated DC/DC converter is typically integrated on the board to act as a switching mode power supply (SMPS) and transform the incoming low voltage power supply from the vehicle (12 -24V), to the voltage required by the gate driver. The SMPS is also used to feed the other larger sub circuits and integrated circuits, both on the driver board and on the logic board (Infineon, 2014b). There may be additional logic circuits on the driver board to interpret various sensor signals and govern different protection measures, for example to measure the voltage on the DC link and the temperature in the power...
module. However, the temperature sensors themselves are located in power module, e.g. integrated in one or more of the chips (Infineon, 2012a, 2014b). Finally, the driver board requires a connector as a single interface to the many ports of the logic board. The auxiliary terminals of power module, one for each IGBT terminal and two per temperature sensor, must also be coupled to the board, for example using board to board pin connectors.

Data collection

Data for modelling the driver board was collected from Infineon (2012a, 2014b). The two printed circuit boards (PCBs) of the baseline units were compared. Both were found to be 1.5 dm³ in size, with the same number of functional blocks and almost identical block structure, despite the difference in power capability of the coupled power modules. Both PCBs were identified to be of standard FR-4 type, built in six layers with surface finish for lead free surface mount components, i.e. matching the dataset for lead free surface mount boards in the Ecoinvent database (Hischier et al., 2007, Weidema et al., 2013). This board type weighs 32.6 g/dm³ (Hischier et al., 2007), and it consists of roughly 40% glass fiber, 40% epoxy resin and 20% copper foil (Nan Ya Plastics, 2008). It also has a surface finish referred to as a solder mask, on average representing around 0.1% of its weight (Hischier et al., 2007). The mass of a 1.5 dm³ board was found to be 49 grams, divided into 20 grams of glass fiber, 20 grams of epoxy resin and 9 grams of copper foil (a low estimate which was balanced by a high estimate for the logic board copper share).

The number of electronic subcomponents (often referred to as surface mount devices, SMDs) on the two boards were counted and compared. It was found that the driver board of the small baseline unit had 386 SMDs whereas the board of the large baseline unit had 316 SMDs. The number of pin connections between the auxiliary terminals of the power module and the driver board were counted to 16 for the small baseline unit and 18 for the large. Overall the two boards were judged to be very similar, and there was no indication of an increasing board size or larger number of SMDs with higher power requirements of the inverter unit.

Nevertheless, some main components in the driver circuits could be expected to scale with the power demand of the module. As a check, key transistors and capacitors in the driver circuits were identified on both baseline driver boards. The circuit designs were found to be analogous and the key devices of similar size, in some cases identical. Also, a simple linear scaling test was conducted for the devices expected to scale in size when controlling smaller or larger IGBTs in the power module, with the SMD arrangement of the large reference driver board as the starting point. It was found that the designated components only altered the total mass of the board with 5-6 grams when scaling from 20 to 200 kW.

Hence, in order to reduce complexity, it was selected to model the reference driver board of the LCI model as constant, i.e. with the same board size and the same number of SMDs over the entire span of model parameters, based on the bill of materials for the large baseline driver board (Infineon, 2014b). Next, all SMDs on that board were classified in type based on the electronic component categories available in the Ecoinvent database (Hischier et al., 2007, Weidema et al., 2013) and in size based on their package code (Topline, 2016). Mass references per type and size were collected to establish the total mass of each SMD category on the board. A compilation of the result is shown in Table 4, and the total mass of the driver board components was calculated to be 65 grams. A more detailed account of the classification, including mass references for each SMD package size and type, are presented in Appendix A.

The amount of Sn95.5Ag3.9Cu0.6 lead free solder used for the driver board was calculated to match a component density representative for a PCBs used in an automotive application, with 20% of the total board area consisting of pads which are soldered to connect the components (Edgren, 2015). A more detailed description of the data collection and calculation procedure is given in Section 5.1.3. The average amount of solder applied per square meter of board area, for reflow soldered and surface mounted devices, was found to be 75 g/m². Hence, the total amount of solder for the driver board was calculated to 1.1 grams.

Finally, the driver board has conformal coating of polyurethane lacquer on both sides of the board. The mass was calculated to 1.2 grams (see Section 5.1.3).

---

10 Functional blocks here refer to a set of board components which fulfill a specific function together.
11 Three pins for each switch in the power module – one per IGBT terminal – plus temperature measurement in one (small reference module) and three (large reference module) of the active chips, respectively.
12 A standard code referring to the component's physical shape and outline.
<table>
<thead>
<tr>
<th>Device type</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor, electrolyte type, &lt; 2cm height</td>
<td>2.8 g</td>
</tr>
<tr>
<td>Capacitor, for surface-mounting</td>
<td>2.2 g</td>
</tr>
<tr>
<td>Capacitor, tantalum-, for through-hole mounting</td>
<td>2.2 g</td>
</tr>
<tr>
<td>Electric connector, wire clamp</td>
<td>18 g</td>
</tr>
<tr>
<td>Light emitting diode</td>
<td>9 mg</td>
</tr>
<tr>
<td>Diode, glass-, for surface-mounting</td>
<td>3.8 g</td>
</tr>
<tr>
<td>Integrated circuit, logic type</td>
<td>3.7 g</td>
</tr>
<tr>
<td>Inductor, miniature radio frequency chip</td>
<td>35 mg</td>
</tr>
<tr>
<td>Resistor, surface-mounted</td>
<td>1.0 g</td>
</tr>
<tr>
<td>Transformer, low voltage use</td>
<td>30 g</td>
</tr>
<tr>
<td>Transistor, surface-mounted</td>
<td>1.3 g</td>
</tr>
</tbody>
</table>

Table 4: The total mass per electronic component type, presented for surface mount devices on the reference driver board, when classified and grouped approximately according to the categories specified in the Ecoinvent 3 database (Hischier et al., 2007, Weidema et al., 2013). For details, please see Appendix A.

4.1.5 Logic board

The logic board mainly consists of a microcontroller block. It also has a low voltage power supply block and several interfaces, both internally, for connection within the unit, to the driver board, to various sensors and measurement circuits, and externally, for connection to components outside the inverter unit, such as the low voltage power supply, the main communication networks of the vehicle and different types of diagnostic and debugging tools.

The role of the logic board is to control inverter unit. The power supply block is responsible for generating all necessary voltages for the logic board components. However, unlike the SMPS on the driver board, it does not have to include isolation. On the other hand, as another safety measure, it contains a timer supervising the microcontroller activity, referred to as a “watchdog”. The logic board supports several different types of sensors to get feedback about the speed and rotation angle of the rotor in the electric machine being controlled, e.g., resolver, encoder, Hall and GMR type sensor (Infineon, 2014b). The microcontroller block holds processing and memory functionality. There are also filters coupled to the different signal ports. The communication interfaces incorporates standard automotive communication interfaces such as RS-232 and CAN (Infineon, 2014b).

Data collection

Data for the modeled logic board was collected from Infineon (2012a, 2014b) for the two baseline inverter units. Analogous with the procedure for the driver board, these boards were compared and found to be 0.9 dm² in size for the small unit and 0.7 dm² for the large unit. Also, the two boards had the same number of functional blocks and identical block structure. As in the case with the driver boards, both were identified to be FR-4 type standard printed circuit boards, i.e. likewise matching the dataset for lead free surface mount boards in the Ecoinvent database (Hischier et al., 2007, Weidema et al., 2013). The number of SMDs were counted to 360 for the small baseline logic board and 457 for the large board. However, also in line with the visual inspection of the driver boards, the two logic boards were judged to be very similar, especially in terms of large and easily identified components. Overall, no clear indication of increasing board or components size was found to follow from higher power requirements of the inverter unit.

Hence, in line with the procedure for the driver board, it was selected to model the logic board of the LCI model as constant, i.e. with the same board size and the same number of SMDs over the entire span of model parameters, based on the bill of materials for the large reference driver board (Infineon, 2014b).

---

13 GMR stands for Giant Magneto Resistance. It is a type of sensor which detects orientation of the magnetic field to determine the angular position of the rotor.

14 A common computer communication interface.

15 CAN stands for Controller Area Network, and it is an automotive (onboard the vehicle) standard communication interface.
Next, all SMDs on the large reference board were classified in type based on the electronic component categories available in the Ecoinvent database (Hischier et al., 2007, Weidema et al., 2013) and in size based on their package code12 (Topline, 2016). Mass references per type and size were collected to establish the total mass of each SMD category on the board, and the total mass of the logic board components was calculated to be 28 grams. A compilation of the results are shown in Table 5, but here is the largest connector excluded since it was remodeled in a later step (see below). The detailed account of the classification, including mass references for each SMD package size and type, are presented in Appendix B.

One component in the logic board reference design was remodeled, the 50 pin external board connector (Infineon, 2014b). The original surface mount connector on the HybridPACK™2 was identified as suitable for an evaluation board setup, but representative of a real application. The mass of the original external, surface mount connector was 3 grams (Harwin, 2012). Instead, it was replaced with data for a larger, panel mount, connector with the same number of pins, and angled legs suitable to mount into the edge of a PCB placed adjacent, or close, to the housing compartment wall. It was assumed that the connector is fastened both in the casing wall, with a gasket on the outside of the wall, as well as soldered by through-hole mounting to the logic board in the final assembly of the inverter unit (see Section 5.5.7), after the rest board has been fully prepared in the surface mounting procedure (see Section 5.1.3). Data for such a connector, TE Connectivity’s Ampseal series, was gathered from Tyco (2010) and TE Connectivity (2017). Two sizes, one 23 pin option and one 35 pin option, were compared to estimate the mass of a 50 pin variant. The comparison resulted in a mass estimation of 49 grams. The connector housing is made of molded plastic, pin conductors of brass and the contacts to the mating connector are gold plated (Tyco, 2010). For the link to Ecoinvent, the larger connector was classified to best match the dataset “electric connector, peripheral component interconnect buss”, with a similar material configuration.

The mass of the unmounted PCB was calculated to 23 grams, with 9 grams of glass fiber, 9 grams of epoxy resin and 5 grams of copper foil (a high estimate to balance out a low estimate for the driver board copper share). Despite the larger number of components on the logic board compared to the driver board, the total pad area16 was judged to be the same per square meter of PCB, due to the smaller component size. It was measured that 7 cm² would be required for the mounting of the larger external connector, and the total amount of lead free solder 0.3 g for through-hole mounting this part to the logic board. The procedure is further described in Section 5.6.1. The lead free solder for the surface mounted components was calculated to 0.5 g when applied on 0.7 dm² of board area, based on the data presented in sections 4.1.4 and 5.1.3.

Finally, the logic board has conformal coating of polyurethane lacquer on both sides of the board. The mass was calculated to 0.6 grams (see Section 5.1.3).

<table>
<thead>
<tr>
<th>Device type</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor, electrolyte type, &lt; 2cm height</td>
<td>3.7 g</td>
</tr>
<tr>
<td>Capacitor, for surface-mounting</td>
<td>1.9 g</td>
</tr>
<tr>
<td>Electric connector, wire clamp</td>
<td>4.8 g</td>
</tr>
<tr>
<td>Switch, toggle type</td>
<td>300 mg</td>
</tr>
<tr>
<td>Light emitting diode</td>
<td>11 mg</td>
</tr>
<tr>
<td>Diode, glass-, for surface-mounting</td>
<td>540 mg</td>
</tr>
<tr>
<td>Integrated circuit, logic type</td>
<td>6.5 g</td>
</tr>
<tr>
<td>Integrated circuit, memory type</td>
<td>36 mg</td>
</tr>
<tr>
<td>Inductor, miniature radio frequency chip</td>
<td>350 mg</td>
</tr>
<tr>
<td>Inductor, low value multilayer chip</td>
<td>18 mg</td>
</tr>
<tr>
<td>Inductor, ring core choke type</td>
<td>5.7 g</td>
</tr>
<tr>
<td>Resistor, surface-mounted</td>
<td>300 mg</td>
</tr>
<tr>
<td>Transistor, surface-mounted</td>
<td>540 mg</td>
</tr>
</tbody>
</table>

Table 5: The total mass per electronic component type, presented for surface mount devices on the reference unit logic board, when classified and grouped approximately according to the categories specified in the Ecoinvent 3 database (Hischier et al., 2007, Weidema et al., 2013). For details, please see Appendix B. The external board connector is not included in this table, since it was remodeled to a larger type.

---
16 The pads are the terminals of the PCB and constitute the actual area of the PCB being soldered.
4.2 Casing, cooling and uniting parts

4.2.1 General description and data for the housing compartment

The electronic subparts of the inverter are mounted into a casing unit, generally made of aluminum (Burress et al., 2009, Infineon, 2010c, Burress et al., 2011, Infineon, 2012a, Volke and Hornkamp, 2012). It protects the electronics from the surrounding environment and constitutes a frame, both for internal mounting of subparts, and for mounting the unit in the vehicle. Different terms are used, meaning almost the same thing: house, housing, compartment, frame and casing. These terms are often used interchangeably, but here we make a distinction, to provide a clearer description. “Casing” or “house” refers to the complete subpart, including a heatsink for cooling functionality. The heatsink is discussed separately in sections 4.2.2 and 4.2.3, but it is often integrated a part of the casing design (Burress et al., 2009, Burress et al., 2011, Burress and Campbell, 2013). The “housing compartment”, “compartment”, or “enclosure” refers to the space and walled section of the house where the electronic components are installed. It has a cover to enclose the section. “Frame” refers to the structural aspect of the casing unit and its functionality for fixation.

The design of the compartment and the cooling arrangement is a delicate engineering balance which governs the overall electric and thermal performance of the inverter unit, its volume and its ease of assembly. Most importantly from an LCI point view, it is the heaviest subpart, but its share of the total weight can vary greatly, making it very hard to capture in a generic model. Inverter efficiencies are high, within 97-99%, when operating at high power, close to the nominal rating (Burress et al., 2009, Burress et al., 2011, Burress and Campbell, 2013, Miller, 2013b, Rogers, 2013). Still, even though losses are relatively small, there is a large difference if the heatsink is cooled with a liquid or using air. Liquid cooling is more efficient. There are numerous interrelated design options for the casing to achieve sufficient cooling, high density internal packing and well-fitted installation together with other units of the powertrain.

Furthermore, in passenger cars it is common that more than one power electronic unit, e.g. the motor control inverter and different types of dc-dc converters, are mounted together within the same house and share several subcomponents, such as DC link capacitors and bus bars for current conduction (Burress and Campbell, 2013). As an example, the 2010 version of the Toyota Prius’ power control unit (PCU) gathers two separate inverters, one for motor control and one for generator control, one boost dc-dc converter and one 200 V-12 V step-down dc-dc converter in the same liquid cooled compartment (Burress et al., 2011). The 2008 Lexus LS 600H has a similar, but larger, integrated PCU (Burress et al., 2009). In general, this allots a smaller share of the housing and cooling for each integrated power electronic unit compared to the compartment of a stand-alone unit.

Data collection

The underlying data for the calculation of the total casing weight was established in two separate steps for the LCI model. First, the volume and mass of one small reference housing compartment and one large reference housing compartment was estimated, matching the electronic subparts in size at 20 kW and 80 kW. In a second step, similar reference data for one small, and one large heatsink, was calculated for each of the two cooling options. This data collection is discussed further in sections 4.2.2 and 4.2.3.

For the compartment, existing automotive inverter units described literature were visually inspected from photographs to estimate internal packing distances and the space required for cable terminals using glands or similar entries (Burress et al., 2009, Burress et al., 2011, Burress and Campbell, 2013, Miller, 2013a). Information was gathered from Johansson (2015) that the wall thickness of aluminum casings for automotive power electronics likely span within 4-5 mm. Next, drawings and masses for six standard die cast aluminum enclosures for electronics with a wall thickness of 4 mm was collected from Rose Systemtechnik GmbH (2016), including lid, structural details and bulk mass for mounting the lid with screws, providing strength et cetera. The data was used establish one small and one large reference housing compartment (conforming to the 20 kW and 80 kW reference units), as an integrated component enclosure section of a complete casing (with the heatsink as the other integrated section) made by die casting, see Section 5.4.2. The data from Rose (2016) was compared with the free space required for mounting the electronic subcomponents of the two baseline units (Infineon, 2012a, 2014b). Holes for mounting cable glands and the fact that the heat sink provides the bottom to the compartment was also considered in the weight calculation. The resulting inner volumes and masses of the two reference compartments are shown in Table 6. The aluminum mass scale factor for the housing compartment was calculated to 10.2 g/kW of nominal inverter power, with the mass of the small reference unit as the starting point.
The options for air or liquid cooling systems, described in subsequent sections 4.2.2 and 4.2.3, have been assessed based on the requirements of the two baseline units in order to provide sufficient cooling for continuous operation in various ambient temperatures, in line with the discussion presented in Section 3.4. The maximum power rating used for the calculations corresponds to 150% of the nominal value, a reasonable but rough estimate selected to match a 10 second temporary thermal overload.

### 4.2.2 Liquid cooled heatsink

A heatsink for a liquid cooling system must have sufficient bulk to allow for cavities, channels or flow patterns as well as screw mounting of the power module. It must include an inlet and an outlet in a suitable direction from a packing point of view.

The cooling system also requires a coolant circuit with hoses and a pump. A mix of 50% water and 50% ethylene glycol is a common cooling liquid for automotive power electronics (Burress et al., 2009, Burress et al., 2011, Infineon, 2011, Miller, 2013b). The liquid is pumped around in looped channels or larger cavities in the heatsink. Typical figures are a flow rate of 10 liters per minute with a pressure drop of 100-200 pascal over the cooling circuit (Infineon, 2010a, 2011, Rogers, 2013). In a regular setup the baseplate of the power module acts as a heat spreader and the heatsink as the interface for heat exchange with the cooling medium. The two parts are screwed together and a thermal interface material (TIM), also referred to as thermal grease, is applied as an intermediate layer to guarantee full contact and that the thermal contact resistance is kept as low as possible (Fuji Electric, 2015, Infineon, 2010b). A typical layer thickness is 100 µm, and the main constituents of TIMs recommended for power electronics are silicone oil and zinc oxide, but aluminum oxide is also used (Volke and Hornkamp, 2012, Fuji Electric, 2015).

Still, this layer has a limiting effect on the performance and research efforts are made to improve the TIM as well as finding ways to remove the interface and cool the power module directly (Rogers, 2013). For example, one version of the power module for the 80 kW baseline unit comes with a “pin-fin” structured baseplate. It is supposed to be mounted directly into the cooling cavity of the heatsink and sealed using an O-ring. This yields very effective cooling (Infineon, 2010c). However, the direct application of pressure on the baseplate increases the risk for damage to the power module and leakage of cooling liquid (Infineon, 2010a).

#### Data collection

The liquid cooling heatsink reference mass was established by combining the estimated length and width of the housing compartment with data for the recommended cooling designs for the 20 kW and 80 kW baseline units (Infineon, 2012a, 2010c). A thickness of 2.5 cm recommended for cooling plate of the small reference unit was used for whole range of 20-200 kW nominal power. Additional information was gathered from a visual display of the Nissan Leaf cooling circuit, presented by Burress and Campbell (2013), and used together with the Infineon drawings to analyze the amount of cavity in channels leading to inlets and outlets, and within the cooling circuit. It was estimated that roughly 50% out of a 1 cm thick section throughout all of the cooling.

<table>
<thead>
<tr>
<th>Reference unit</th>
<th>Volume</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>1.8 dm³</td>
<td>1.7 kg</td>
</tr>
<tr>
<td>Large</td>
<td>2.6 dm³</td>
<td>2.3 kg</td>
</tr>
</tbody>
</table>

Table 6: Housing compartment inner volume (free dimensions for mounting) and its share of the casing mass (including lid, walls and structural details but without a bottom where the heatsink is integrated directly from die casting, see Section 5.4.2) for the small and large reference inverter units.
block is void. It can also be assumed that a cooling block is manufactured in two parts, one joined with the housing compartment and one making up a lid for the cooling section. Both parts will then be joined by screw mounting into threaded holes. It was assumed that the void estimation includes these holes as well. The results for one small and one large reference heatsink for liquid cooling are presented in Table 7. Next, these reference points were used to establish a linear scale factor for the heatsink mass of 13.6 g/kW over the 20-200 kW span, starting from the small reference unit heatsink mass.

<table>
<thead>
<tr>
<th>Reference unit</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>2.1 kg</td>
</tr>
<tr>
<td>Large</td>
<td>2.9 kg</td>
</tr>
</tbody>
</table>

Table 7: The mass of the small and the large reference heatsinks for liquid cooling, and their contribution to the complete casing’s mass in the small and large reference inverter units.

Next, data for the amount and composition of the thermal grease was collected. A silicone paste with a thermal conductivity of 3 W/m·K (Electrolube, 2014) was found representative. About 60-80 % of its weight consists of aluminum oxide and 10-30% of zinc oxide, with the remainder as silicone oil (Electrolube, 2013, Volke and Hornkamp, 2012) and the density is 3.0 g/cm³ (Electrolube, 2014). Hence, the composition was set to be 70% aluminum oxide, 15% of zinc oxide and 15% silicone oil. The amount of TIM was calculated to match the mountable inner bottom surface areas of two reference housing compartments, assuming a 100 µm thick layer for both units. The starting mass for TIM at 20 kW nominal inverter unit power was found to be 9 grams, and the scale factor 70 mg/kW.

4.2.3 Air cooled heatsink

Air cooling is often accomplished using fins which mainly disperse heat through convection (Volke and Hornkamp, 2012). Simple ventilation requires a large heatsink whereas forced convection using a fan makes it possible to reduce the fin size considerably. Natural convection means that a volume of air at the surface of the heatsink absorb heat energy and becomes less dense, rise and shift away to be replaced by another, unheated volume of air, inducing a flow referred to as a convection current. In order to achieve more efficient cooling the convection can be forced, using some type of fan (Lee, 1995b, Volke and Hornkamp, 2012). Heatsinks are generally designed to achieve a large surface area for the heat exchange to take place. The reason is that heat transfer across the interface between the solid surface and the coolant air normally is the greatest barrier for heat dissipation (Lee, 1995a). Hence, the use of fins is a way to maximize the air cooled convection by providing a large surface area (Volke and Hornkamp, 2012).

A heatsink also radiates heat. In natural convection, both the distance between fins and the surface area finish is important for the performance. For example, aluminum may be anodized to achieve high radiation emittance (Volke and Hornkamp, 2012). In the case of a forced flow above 2 m/s this effect is negligible, and surface treatment can be omitted (Lee, 1995a, b, Austerlitz, 2014, Volke and Hornkamp, 2012). However, other important factors for the performance are the fin length (defining the heatsink height), the heatsink width and length, and airflow speed (Austerlitz, 2014). The heatsink size can be reduced with increasing air speed, e.g. dimensioning for 4 m/s requires only a fourth of the heatsink size compared to natural convection. On the other hand, for speeds above 7-8 m/s this effect is reduced considerably when reaching down to about 20% in heatsink size compared to that of natural convection (Austerlitz, 2014, Volke and Hornkamp, 2012). Also, the performance varies differently depending on if it is the width or the length of heatsink which is adjusted. Roughly, it increases linearly with the heatsink width perpendicular to the flow, whereas it follows the square root of the heat sink length parallel to the air flow (Lee, 1995a).

Hence, a rational setup for air cooling is that there is a fan which can provide the required air speed and that the unit is oriented and scaled in such a way that the cooling capacity increase linearly with the geometry, i.e. with the heatsink oriented such that the width matches the longest side of the casing. Additionally, the mounting of the power module on the heatsink can be expected to be identical to the procedure presented for liquid cooling, with screw mounting and using a TIM.
Data collection

The weight of the air cooled heatsink was based on data from Austerlitz Electronics GmbH (Austerlitz, 2014). They offer air cooling profiles for forced cooling made from an Al-MgSi alloy. It is an alloy suitable for extrusion consisting of 98.8% aluminum blended with mainly silicon and magnesium, as the name indicates (OKW, 2014). The density is stated to be the same as for pure aluminum (2.70 g/cm³) and the thermal conductivity somewhat lower (210 W/m·K compared to 238 W/m·K) (Nordling and Österman, 1996, OKW, 2014). Thus, a pure aluminum heat sink was assumed in order to align the material selection with that of the housing compartment and available upstream data in the Ecoinvent database (Weidema et al., 2013). This assumption was judged to well-motivated since the material properties makes a good match with the heatsink design specifications, and that the assumed manufacturing methods differs (see Section 5.4.2).

A standard model heatsink, 253 mm wide (QLS 253.3), was identified as a representative design and selected as a starting point for the calculations (Austerlitz, 2014). The fin height is 62 mm extending from a 16 mm bulk platform, and the length to weight relationship is 219 g/cm. The length of the heatsink, i.e. the direction parallel to the air flow, was set to match the width of the casing, given by the geometry estimation in Section 4.2.1. The cooling performance of the heatsink was established by studying a diagram of allowed increase in the heatsink temperature versus the capability of cooling off dissipated power, rated for an air flow of 170 m³/h (Austerlitz, 2014). This flow corresponds very well to an air speed of 3 m/s for the selected profile cross-section (Austerlitz, 2014).

Furthermore, it was judged that the heatsink must be able to cool off 2.5% thermal losses continuously, based on the specified maximum power dissipation of the 80 kW baseline power module (Infineon, 2011), with an added margin for losses from other subcomponents and for thermal time constants. Hence, the required cooling capacity was calculated to be 500 W for the 20 kW baseline unit and 2 kW for 80 kW baseline unit. Also, when using a fan with an inlet for external air, it is a reasonable to set the upper limit of the ambient temperature to 45°C (Lee, 1995a). In such a case, a requirement that the boundary between the TIM and the power module may not exceed 75°C, implies that the temperature increase in the entire cooling block, including 2-3 K in the TIM, can at most be 30 K while cooling at full capacity.

Turning back to the rated performance curves and matching the geometry of a preliminary small reference heatsink to that of the small reference housing compartment, it was found that it would be able to cool off more than 600 W of dissipated power and still stay within an allowed 30 K temperature increase, already at 3 m/s air speed. Oppositely, for the large reference unit, the preliminary heatsink cooling capacity was found to be 850 W at 3 m/s air speed. However, a cooling fan is typically sized to provide the same type of air flow under the hood of the vehicle, as high speed driving provides, but for low speeds and at standstill. The speed of air behind the inlet to the radiator in a passenger car is typically more than 7 m/s when the vehicle is driving 100 km/h (Jama et al., 2004). After an adjustment of the maximum air speed, using a correction factor presented by Austerlitz (2014), it turned out that the same preliminary heatsink for the large reference unit would be able to cool off more than 1.5 kW, but not the required 2 kW. In order to do so, the base of the heatsink would have to be 30% wider than the casing geometry, which was found unreasonable. Still, the mass of the heatsink for the large reference unit was calculated and used a reference point in the subsequent step together with the small reference heatsink, to establish scale factors for the air cooling heatsink. But, based on iterative checks of the cooling requirements and overall casing geometry, it was estimated that air cooling is a reasonable alternative only up to about 50 kW nominal power of the inverter unit.

In addition, a higher top air speed also made it possible to downsize the final design of small reference heatsink. In fact, the heatsink was scaled down to 45% of its original width, still cooling more than 500 W at 7 m/s. This downsized heatsink was used to calculate the mass of the heatsink for the small reference unit. However, it should be regarded as an engineering estimation for a reasonable mass of the heatsink and not as a plausible actual design. In a real case, the full base area would likely be used but less fins with shorter length.

In summary, air cooling can only be selected for the LCI model calculations, if the power of the unit falls within the range of 20-50 kW. It also implies that the inverter unit is accompanied by a fan with a top speed of 7 m/s, which is not included in the model. The scale factor for the heatsink mass was calculated to 69.8 g/kW for this span, starting from the small reference unit heatsink mass. Table 8 shows the value for both reference units, although the large unit in this case is not a part of the valid span for air cooling.
<table>
<thead>
<tr>
<th>Reference unit</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>3.8 kg</td>
</tr>
<tr>
<td>Large</td>
<td>5.3 kg</td>
</tr>
</tbody>
</table>

Table 8: The mass of the small reference heatsink for air cooling, and its contribution to the complete casing’s mass in the small reference inverter unit. The large reference unit is outside the valid span for air cooling in the model, but the heatsink mass still represents the upper reference point for the scale factor calculation.

### 4.2.4 Casing surface coating

Vehicles operate under corrosive conditions, for example by road salt which can deteriorate powertrain components and shorten their lifetime. Consequently, although aluminum have inherent corrosion resistance, it is common that enclosures are painted to provide additional protection (Rose, 2016). Automotive power electronic casings often have a similar exterior as the motor housing, and sometimes the two are integrated (Burress et al., 2009, Burress et al., 2011, Shimizu et al., 2013). Hence, surface coatings applied on motor housings are also used for casings of power electronic motor control units. Typically, thermally conductive coatings are used, for example acrylic varnish, enamel, alkyd or epoxy-based paints, with a thickness of around 0.5 mm (Tong, 2014).

However, aluminum casings can also be protected without being painted. Another common surface treatment method is anodizing (Davis, 1993, SAF, 2016). It is a technique to create a protective layer of aluminum oxide on the surface of the base metal. The oxide layer is hard, durable and resistant to weather and corrosion. Anodized coatings can also be colored by dyeing the oxide layer. Otherwise it becomes colorless transparent or exhibits a bronze color, depending on the exact aluminum alloy composition. Anodizing is more common for extruded parts than casted, but can be used for both (Davis, 1993). A typical coating thickness is in the range of 15-50 µm (Davis, 1993).

#### Data collection

It was assumed that two different coatings methods are applied depending on if the heatsink is cooled with liquid or air. It was observed that standard aluminum enclosures for electronics are often painted (Rose, 2016), whereas anodizing is the default coating option for many air cooled heatsinks (Austerlitz, 2014).

Hence, a clear varnish was selected for the coating of the liquid cooled aluminum casing. Data was gathered from ExxonMobil (2007) and Von Roll (2013) for an alkyd resin based coating intended for electrical machine housings and similar applications. The varnish mass was calculated for a 0.5 mm thick layer, when dried, by comparing the density of the liquid paint and density of the solvent share, for a 48% solvent mass share in the paint (ExxonMobil, 2007, Von Roll, 2013). It was combined with an estimate of the housing compartment and the heatsink outer surface area. Table 9 shows the results for the different parts of the casing for the two reference inverter units. The starting mass for paint came to a total of 79 grams and the scale factor to 385 mg/kW. For further details about the amount of paint applied in liquid state, see Section 5.4.4.

The air cooled casing was modeled to be anodized, both the heatsink and the housing compartment, on the inside as well as the outside, since the whole part is immersed in a bath during the process. However, the inside bottom area of the housing compartment was assumed to be masked during the process, so that the TIM still forms the only layer between the baseplate of the power module and the heatsink, in accordance with the heat sink sizing calculations. The aluminum oxide layer was assumed to be 20 µm thick, making a negligible shift of the total mass of the casing. However, the surface area has been estimated, to enable calculation with the dataset for anodizing described in Section 5.4.5. Values for the reference units are presented in Table 10. The scale factor anodizing area was calculated to 2.5 dm²/kW for the 20-50 kW span, starting from the 70 dm² casing surface area of the air cooled small reference unit.

<table>
<thead>
<tr>
<th>Reference unit</th>
<th>Housing compartment</th>
<th>Liquid cooled heatsink</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface area</td>
<td>Varnish mass</td>
</tr>
<tr>
<td>Small</td>
<td>9.1 dm²</td>
<td>47 g</td>
</tr>
<tr>
<td>Large</td>
<td>11.7 dm²</td>
<td>60 g</td>
</tr>
</tbody>
</table>

Table 9: Estimated outer surface area of the aluminum casing parts and the resulting varnish mass, for the liquid cooling option of the two reference inverter units.
The need for power distribution to and from the subcomponents of the inverter unit is generally solved with a laminated bus bar. The complete distribution network is brought into one single structure instead of using multiple bus bars or wires as conductors. There are many benefits of this integration of all conductors into one subpart. Electrical performance and reliability is improved, while cost is reduced (Allocco and Whistler, 1996, Mersen, 2013). Additionally, it allows very compact design and provides structural functionally to the unit. (Mersen, 2013).

Typical conductor materials are copper or aluminum, or alloys of these metals (Mersen, 2013). However, the unique feature of the laminated bus bar are the thin foils of dielectric insulation between the conductors. It allows them to be structured in layers which are only a fraction of a millimeter apart (Storm, 2016). Examples of common insulation materials are polyvinyl fluoride (PVF)\(^\text{17}\), polyamide polymer paper\(^\text{18}\), and polyethylene terephthalate (PET)\(^\text{19}\) (Stigben, 2004, Mersen, 2013, Storm, 2016). Generally, the lamination layer extends outside the edge of the bus bar layer on all sides to provide sufficient insulation. The construction at the edges can be open, filled with glass or epoxy, or sealed by uniting the overshooting insulation layers (Mersen, 2013, Storm, 2016).

Laminated bus bars are easy to mount compared to other conductor solutions. They are manufactured specifically to match the fixation and connection points of the other subparts, and prepared with threaded holes when required (Mersen, 2013). For instance, in connection to a cable gland there may be a small termination block adapted to the incoming wire. Also, bus bars often have a surface finish to improve the electrical properties of the termination. Plating with tin or nickel of the conductors’ surface area is common (Mersen, 2013). Standard plating thicknesses for nickel are within 5-40 µm (AST, 2012). Silver or gold are sometimes also applied, but then only on the terminal surface, to reduce the cost (Mersen, 2013).

Turning to the size of the conductors, it is related both to electrical parameters and the geometry of the inverter unit. Naturally, conductor lengths depend on distance between the terminals to be interconnected. Each conductor cross section area relates to the maximum current it must be able to handle, both on the DC link side and for the AC phase currents (Stigben, 2004, Mersen, 2013). According to Mersen (2013), the rule of thumb is that each conductor should be designed to handle 5 A/mm\(^2\), with an additional 5% increase of the cross section for every adjacent conductor layer. Hence, a formula for the cross section area (given in mm\(^2\)) of each bus bar layer can be formulated\(^\text{20}\):

\[
\text{Cross section area} = I_{\text{MAX}} \times 0.2 \times (1 + 0.05 \times (N - 1)) \\
\text{(Eq. 8)}
\]

where \(I_{\text{MAX}}\) is the maximum current for which the conductor is designed, on the DC link side as well as on the AC side, stated in ampere. However, for AC at high frequency, the current flows only close to the surface of the conductor (Mersen, 2013). As a result, the thickness must be limited to make use of the full cross section. \(N\) represents the number of adjacent bus bar layers.

Compared to other applications, 5 A/mm\(^2\) is a relatively cautious rule of thumb. For example, electric traction motor designs can accept phase current densities up to 20 A/mm\(^2\) in the stator windings (Nordelöf et al., 2018). On the other hand, during the switching operation of the power module, it can be expected that very high phase currents occur occasionally, for short periods of time. Therefore, in line with the general description

<table>
<thead>
<tr>
<th>Reference unit</th>
<th>Housing compartment</th>
<th>Air cooled heatsink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>18 dm(^2)</td>
<td>52 dm(^2)</td>
</tr>
<tr>
<td>Large</td>
<td>24 dm(^2)</td>
<td>198 dm(^2)</td>
</tr>
</tbody>
</table>

Table 10: Estimated surface area of the aluminum casing parts (outside and inside of housing compartment and heatsink with fins) subject to anodizing, for the air cooling option of the two reference inverter units. The large reference unit is outside the valid span for air cooling in the model, but the surface area still represents the upper reference point for the scale factor calculation.

---

17 Trade name Tedlar.
18 Trade name Nomex.
19 Trade name Mylar.
20 The original expression was given in square inches and the rule of thumb is 400 circular mils per ampere.
of inverter unit design in Section 3.4, it is practical that the laminated bus bar is constructed with a performance margin and that it can be thermally overloaded temporarily and then return to steady-state operation without being damaged or degraded. Heat is buffered, and dissipated later, when the phase current is lower. Hence, practically, the rule of thumb can be used as a guide for sizing both DC and AC conductors in the bus bar structure when matching the maximum currents for longer peak power operation. In the following, appropriate theory is presented for estimating such conditions.

The definition of electrical power gives that the maximum DC link current will occur at the lowest possible system voltage, during peak power operation. A typical DC voltage source of a traction inverter is a lithium-ion battery of some type. The full discharge voltage level for common lithium-ion chemistries, expressed relative to the nominal rating, range from 75-83% (Battery University, 2016). Below this level the battery is fully depleted and the voltage supply will be cut off. Thus, the maximum DC current can be calculated as:

\[ I_{DC-MAX} = \frac{P_{DC-MAX}}{U_{DC-Cut-off}} \]  
(Eq. 9)

Next, turning to the three phase AC side, the power equation expressed in phase voltage and phase current (Eccles, 2011), states:

\[ P_{AC} = 3 \times U_{Phase} \times I_{Phase} \times \text{power factor} \]  
(Eq. 10)

where the power factor is a value between 0 and 1 depending on the phase angle. For a common pulse width modulation (PWM) strategy, with a high usage of the provided DC link voltage (Josefsson, 2015):

\[ U_{Phase} = m \times \frac{U_{DC}}{\sqrt{3}\sqrt{2}} \]  
(Eq. 11)

The expression includes the modulation index \( m \), which reach unity when the DC voltage is fully output into the created AC voltage. Combining Eq. 10 and 11, and rearranging, gives

\[ I_{Phase} = \frac{2}{3} \times \frac{P_{AC}}{m \times U_{DC} \times \text{power factor}} \]  
(Eq. 12)

Both \( m \) and the power factor are governed by conditions outside the inverter, and depend on the load from the electric motor being controlled. Typically, \( m \) is close to one when the unit is supplying peak power. However, Josefsson (2015) argues that 0.9 is a reasonable value for the conversion of DC to AC, to guarantee controllability of the current. For the power factor, Rabiei (2015) showed that it is also about 0.9, or higher, during supply of maximum power to a permanent magnet synchronous machine. Combining these values into Eq. 12 and recognizing, as for the DC link, that the maximum phase current for peak power operation will occur when the DC system voltage is as low as possible, gives

\[ I_{Phase-Max} \approx 1.0 \times \frac{P_{AC-MAX}}{U_{DC-Cut-off}} \]  
(Eq. 13)

Eq. 9 and 13 indicate that with high overall efficiency, i.e. a small difference between \( P_{DC-MAX} \) and \( P_{AC-MAX} \), there are roughly equal requirements for the cross section areas of the DC and AC conductors.

---

21 This span is based on cell data for six different lithium-ion battery chemistries: LiCoC\(_2\) (LCO), LiMn\(_2\)O\(_4\) (LMO), LiNiMnCoO\(_2\) (NMC), LiFePO\(_4\) (LFP), LiNiCoAlO\(_2\) (NCA), and Li\(_2\)TiO\(_3\) (LTO).

22 This equation is valid when the load is connected in a Y configuration.

23 This theory refers to a PWM strategy called third harmonic injection (THI)-PWM.
Data collection

The data for the bus bar design, and the LCI model calculation procedure for the bus bar, was established in five steps, starting with the theoretical derivation presented above. In line with the general observations, the cut-off DC voltage was set to be 75% of the nominal DC system voltage specified by the LCI model user. Likewise, the maximum inverter power output, i.e. $P_{AC\text{-MAX}}$, was set to be calculated from the nominal power value stated by the user, by scaling it to 150%, in line with the maximum power estimation presented in Section 2.1. Then, $P_{DC\text{-MAX}}$ can be found from $P_{AC\text{-MAX}}$ by taking 2.5% power losses of into consideration, in line with loss estimation presented in Section 4.2.3. Maximum DC and AC currents are calculated using Eq. 9 and 13. It was assumed that the DC conductors would be grouped together in two layers, i.e. $N = 2$, and the AC conductors in three layers, i.e. $N = 3$. Finally, the required cross sections of all conductors can be calculated using Eq. 8.

Next, the total lengths of the DC and AC conductors were calculated by summarizing the conductors in different layers into one length for each type. A geometric estimation was made for the two reference inverter units with 20 kW and 80 kW nominal power rating, based on the topologies presented by Infineon (2010b, 2012c) for IGBT Module Hybrid PACK™1 and HybridPACK™2, combined with the housing compartment estimations presented in Section 4.2.1. All incoming and outgoing connection points, i.e. the location of the cable entries, were assumed to be on the same side of the unit, closest to the AC side of the power module. The values found for the total lengths of both DC and AC conductors, are presented in Table 11. Scale factors were calculated to 1.2 mm/kW for DC side and 0.8 mm/kW for the AC side, with the small reference unit lengths as the starting points.

Subsequently, in the calculation procedure, the total conductor volume is found by combining the lengths and cross section areas, as established from the user input in terms of nominal inverter power and DC system voltage. It is calculated into copper mass using a density of 8960 kg/m$^3$ (Nordling and Österman, 1996). The results for some selected voltages and the complete power range is shown in Figure 12.

<table>
<thead>
<tr>
<th>Reference unit</th>
<th>DC conductor length</th>
<th>AC conductor length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>45 cm</td>
<td>8 cm</td>
</tr>
<tr>
<td>Large</td>
<td>52 cm</td>
<td>13 cm</td>
</tr>
</tbody>
</table>

Table 11: The summarized lengths of the DC and AC conductors within the laminated bus bars of the small and large reference inverter units. The length estimation was made to match the inverter topology and fixation points presented in the Infineon (2010b, 2012c) reference data, in combination with the housing compartment.

Figure 12: Estimated DC bus bar copper mass over the complete model power span, 20-200 kW, for some selected voltage rating values, based on the established mass scaling model.
In the fourth step, in line with the general observations, it was assumed that the surface finish consist of electroplated nickel. The conductor thickness was assumed to scale in thickness from 1 mm for the lowest found maximum currents to 8 mm for the highest currents, both on the DC and AC sides, making it possible to calculate the total surface area of the conductors. The plating thickness was set to 20 µm and the nickel mass was calculated using a density of 8900 kg/m³ (Lagneborg and Waltersson, 2004). The results for nickel mass of the bus bar, for some selected voltages and the complete power range, is shown in Figure 13.

Figure 13: Estimated DC bus bar nickel mass, over the complete model power span, 20-200 kW, and for some selected voltage rating values, based on the established mass scaling model.

Figure 14: Estimated DC bus bar polyethylene terephthalate (PET) mass, over the complete model power span, 20-200 kW, and for some selected voltage rating values, based on the established mass scaling model.
Finally, in the last step for the bus bar, the insulation material was assumed to consist of two layers of PET between adjacent conductors and one single layer at the top and bottom, i.e. matching one layer on each side of the total conductor length. Furthermore, based on observation in part catalogues, the foils were assumed to overshoot the copper surfaces with about 5% on all sides. Data for a 350 µm thick MYLAR foil with a mass of 487 g/m² was gathered from Caribex (2015). The results for PET mass of the bus bar, for some selected voltages and the complete power range, is shown in Figure 14.

4.2.6 Cable glands

Cable glands are used to provide sealed cable entries into the housing compartment for the DC current conductors coming from the battery, and for the AC current conductors going from the inverter unit to the electrical machine. The gland body is threaded and mounted into the casing wall by screwing. An o-ring seal the thread hole from moisture. In advance, the cable has been stripped from its outer insulation and inserted into the cable gland, surrounded by a sealing gasket and also often an insert with a lamellar cage. The latter make sure that the cable shield can be properly unfolded and connected to a suitable ground point to avoid that electromagnetic interference is emitted to other parts and components (Agro, 2011). Figure 15 shows a sketch of a cable gland cross section, suitable to mount into an inverter unit casing wall.

Cable glands are typically made of brass, stainless steel, aluminum or polyamide²⁴ (CMP, 2015, Eaton, 2015, Ouneva, 2015, Fibox, 2016). In the case of metal glands, the insert is still often made of polyamide²⁴ plastics (Lapp, 2012, Fibox, 2016). In environments requiring high resistance to corrosion, it is common to plate nickel on the brass surface. But the coating layer is thin, with a thickness of 5-7 µm, since there are many threaded surfaces with narrow tolerances (Eaton, 2015). Seal materials for o-rings and gaskets are various thermostet elastomers (heat resistant rubber-like materials) such as neoprene or silicone (Thomas & Betts, 2005, CMP, 2015, Eaton, 2015).

Data collection

Data for five nickel plated brass cable glands was gathered from CMP (2015), Ouneva (2015), two for the DC link cable connections and three for the AC cable connections to the electric motor. It was found that M16

![Figure 15: Cross section sketch of a cable gland with the inside of the casing to the left of the wall and the external environment of the inverter unit to the right of the casing wall. The arrows indicate the screwing directions of the gland nut (right arrow) and the lock nut (left arrow) onto to the cable gland body.](image-url)

²⁴ In technical information and sales brochures for cable glands the term “polyamide” is often used. Another common term for the group of synthetically produced polyamides is “nylon”.

38
or M20 were suitable sizes\textsuperscript{25} for the glands of the small inverter reference unit, depending on the size of the cable, which in turn relates to the requirements for maximum currents, both for DC and AC, as discussed in Section 4.2.5. Similarly, suitable sizes for the large reference unit were found to be M20 or M25. In both cases, it was decided to use the larger gland for the mass estimation of the model, since the fitting to the cable then can be adjusted with a plastic insert and the rubber gasket, using the same brass gland size. The selection of the larger size can also be regarded as an upper estimate in both cases, but still relevant.

The length of the cable glands on the outside of the casing wall, was found to be in the range of 22-27 mm for M20 size and 22-35 mm for the M25 size. However, both were assessed as extending 25 mm out from the casing wall. The thread length into the casing wall was set to match the wall thickness plus an additional margin of 3-5 mm for the lock-nut. The mass proportion of different substances was estimated in a fixed composition for both M20 and M25 glands, based on a typical geometry in line with Figure 15. The nickel coating layer was set to 7 µm for this estimation. Density data was gathered from Professional Plastics (2005) for a nylon\textsuperscript{24} insert (1350 kg/m\textsuperscript{3}), and a gasket and o-ring of silicone rubber (1250 kg/m\textsuperscript{3}). Brass (64% copper and 36% zinc) and nickel densities of 8300 kg/m\textsuperscript{3} and 8900 kg/m\textsuperscript{3}, respectively, were collected from Nordling and Österman (1996). For the link to Ecoinvent 3 (Weidema et al., 2013) data, glass-filled nylon 6 was selected for the plastic insert (Fibox, 2016), and the seal material was set to match “silicone product”.

The data from the standard parts catalogs combined with the geometric approximation resulted in small and large reference unit masses of 370 g and 540 g for five cable glands, and a scale factor of 2.8 g/kW. The total area for nickel plating was found to start at 5.9 dm\textsuperscript{2} for the 20 kW inverter unit and then scale up to 14 dm\textsuperscript{2} for a 200 kW unit. The composition of the gland is presented in Table 12.

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brass</td>
<td>96%</td>
</tr>
<tr>
<td>Nickel</td>
<td>1%</td>
</tr>
<tr>
<td>Nylon</td>
<td>1%</td>
</tr>
<tr>
<td>Silicone rubber</td>
<td>4%</td>
</tr>
</tbody>
</table>

Table 12: The estimated material composition of a nickel-plated cable gland with a plastic insert and a silicone rubber o-ring and gasket.

4.2.7 Screws, washers and spacers

The assembly of the inverter into one functioning component requires fasteners, typically screws which are secured in threaded holes of the aluminum casing and fixation points in the casing and baseplate of the power module, and in the DC link capacitor. Also, the terminals of the power module and the DC link capacitor are connected to each other and with the bus bar. The driver board and the logic board are mounted onto or placed close to the power module. Galvanized, low alloy carbon steel or stainless steel screws and spring washers are used for this purpose. Plastic clearance spacers, often made of nylon, can be required if the printed circuit boards are mounted on top of each other.

Data collection

Data for fasteners recommended to use when assembling the 20 kW and 80 kW baseline inverter units was gathered from Infineon (2010b, c, 2012a, 2014b), from the kits for HybridPACK\textsuperscript{TM}1 HybridPACK\textsuperscript{TM}2. Since the driver and logic boards of the LCI model were modeled to have the same board size and the same number of SMDs over the entire span of model parameters (see sections 4.1.4 and 4.1.5), the set of fasteners for mounting these two PCBs on top of the power module was also modeled as fixed, i.e. a fixed number of self-tapping screws adapted for direct mounting into thermoplastics with nominal width of 3 mm (Infineon, 2010c). These were approximated in size as M3 slotted head machine screws (DIN 84/85) and spring washers (DIN 6796), with data from Fuller (2013). In line with setup in HybridPACK\textsuperscript{TM}2, it was modeled that the logic board is fastened on top of the driver board, and both are fixated into the power module, using four 25 mm and six 10 mm long M3 screws and four nylon clearance spacers with an outer width of six millimeters.

\textsuperscript{25} Metric size of screw threads such as bolt and nuts, according to ISO 68-1.
Data was also gathered from Fuller (2013) for four 8 mm long M2.5 slotted head machine screws (DIN 84/85) and M2.5 spring washers (DIN 6796), for the fastening of the large external board connector in the housing compartment wall, together with the connector gasket.

Next, it was decided that four 25 mm M6 socket head cap screws (DIN 912) and four M6 spring washers (DIN 6796), again based on data from Fuller (2013), are sufficient for securing the lid of both large and small housing compartments, in accordance with recommended size for fasteners in the standard enclosure documentation (Rose, 2016). Hence, these screws and washers were also included in the fixed set of fasteners. Similarly, it was assumed that the same types and number of screws and washers are required for the liquid cooled heatsink alternative, assuming that the cooling channel arrangement makes it necessary to die cast the heatsink in two parts which must be firmly mounted together. The total fixed weight of the screws and washers for mounting the driver and logic boards, and the complete casing with external connector to the logic board, came to about 2 grams of nylon (assumed to be nylon 6, glass-filled) and 50 g or 85 g of galvanized steel, for the casings with air cooled or liquid cooled heatsinks, respectively.

Finally, the power module and DC link capacitor must be mounted to the baseplate, and the power module, DC link capacitor and bus bar coupled to each other. The bus bar must be connected to incoming cables at terminals next to the cable glands. The number of screws and washers required for all these fastening operations were counted for the small and the large reference inverter units. All screws were set to be 10 mm M6 socket head cap screws (DIN 912) and the washers to be of M6 spring type (DIN 6796), based on the specifications provided by Infineon (2010b, c, 2012a, 2014b). Weight data for screws and washers was collected from Fuller (2013). This share of the fasteners’ mass was expected to scale with the inverter size in the LCI model and the results for the small and large reference units were found to be 100 g and 160 g galvanized steel, and the scale factor of 1 g/kW.

The zinc content in the galvanized steel parts was estimated to 2%, based on a 15 µm coating layer, in line with the findings during the assessment of the zinc content in and the area of galvanized steel parts of the power module. As mentioned in Section 4.1.2, this coating thickness is reasonable for metal goods with threads (Walraven, 2011). Also in line with the assumptions made for the power module, the steel was assessed to be low-alloy carbon steel when matching with Ecoinvent 3 data. Using the estimated fixed zinc mass share and the density of zinc (7130 kg/m³) (Lagneborg and Waltersson, 2004), the total area subject to galvanization could be calculated. It was found to range within 2.8-6.2 dm² for all screws and washers when air cooling is selected, and within 3.5-6.8 dm² when liquid cooling is selected.
5 Assessment of production procedures

5.1 The production of electronic subparts

5.1.1 Semiconductors chips for the power module

The fabrication of the active semiconductor devices of the power module from silicon is an advanced step in power module manufacturing. Initial material preparation is followed by growth of a mono-crystal which is used to make wafers (Williams et al., 2002, Murphy et al., 2003, Volke and Hornkamp, 2012). The highly pure silicon mono-crystal is formed into a rod and provided with a basic doping of suitable elements, e.g. boron or phosphorous (Volke and Hornkamp, 2012). The rod is sliced into wafers, 100-300 mm in diameter, depending on the production setup. The most common wafer diameter is 200 mm (Murphy et al., 2003).

Next, each wafer is fabricated to contain hundreds of semiconductor devices. At the end of the process these are separated from each other by cutting, referred to as dicing26. The wafer fabrication process is highly energy and material intensive (Williams et al., 2002, Murphy et al., 2003). A series of layering, patterning and doping processes in combination with backside metallization and heat treatments are used to design the desired semiconductor device in the wafer. The basic unit operations are: chemical vapor deposition, furnace heating, metallization, cleaning, ion implant, chemical mechanical polishing, photolithography and etching. The term “chip” is used for the finalized and packaged die, after it has been mounted into the intended application (Murphy et al., 2003).

Data collection

The Ecoinvent 3 dataset representing “wafer production, fabricated, for integrated circuit” (Hischier et al., 2007, Weidema et al., 2013) has been selected to model the manufacturing of the semiconductor chips. This dataset couples all necessary processes to bring about silicon wafers from silica sand. However, there are differences between wafers intended for integrated circuits and power IGBTs. The selected Ecoinvent 3 activity describes a method (the Czochralski process) for the initial mono-crystal production which yields slightly too many impurities (Volke and Hornkamp, 2012). Trench field stop IGBTs requires ultra-pure silicon wafers (Volke and Hornkamp, 2012). These are made with a different, floating-zone, method. No data was found comparing the difference for the two methods. Still, the Ecoinvent dataset is likely a high estimate for wafer fabrication in general, in terms of energy use and emissions. Schmidt et al. (2012) evaluated the Ecoinvent dataset and found that semiconductor manufacturing has progressed since this data was collected. Especially, production yields have improved and the use of natural gas has been reduced (Schmidt et al., 2012). Nevertheless, a more in depth examination of improved production procedures for active semiconductor devices and the collection and implementation of more recent data was not included in the current version of the LCI model.

The thickness of a 200 mm wafer was found to be 725 μm (Hischier et al., 2007). Using the density of silicon, 2330 kg/m3 according to Nordling and Österman (1996), gives a wafer weight of 53 g for a 200 mm unit and 1.69 kg/m2. Hence, 1 g of active semiconductor material corresponds approximately to 5.9 cm2 of wafer. Finally, chip dicing is not included in the selected Ecoinvent dataset (Hischier et al., 2007). However, it was estimated to add a very small amount of additional electrical energy even for all chips in the bridge topology, based on data from larger LED chips (Scholand and Dillon, 2012), and was neglected.

5.1.2 DC link capacitor

The standard procedure for manufacturing metallized power film capacitors, as described in Section 4.1.3, is to vacuum deposit a thin layer of zinc or aluminum, or an alloy of the two, as an electrode material on a polypropylene dielectric film (Vishay, 2012, Epcos, 2013, Cornell Dubilier, 2016). The polypropylene film have been prepared beforehand, sliced into a specified width at the end of the extrusion process. After metallization, the film is either stacked or wound into capacitor elements. Wound capacitors are made by rolling the film to a cylindrical roll (Epcos, 2015). Flat windings are made by compressing the cylindrical rolls before they are placed in casings, to fit into the brick package and make better use of its form (Montanari et al., 2008, Epcos, 2015). In the case of metal foil capacitors, the metal foil is fabricated separately and wound together with the plastic film. Stacked-film capacitors are made by winding a “master capacitor” of metallized

26 At this stage each device is referred to as a “die” in singular form, and a common plural form is “dice”.

41
film, or of the combined metal foil and plastic film, on one large ring with a diameter up to 60 cm. Each stacked unit is then cut from the ring and sprayed with metal at the end face (Epcos, 2013, 2015). This is important to connect the electrode layers separately on each side and the internal bus bars, i.e. the conductors leading to the terminals.

The selection of spray metal varies and may, for example, be a tin-copper mixture (Livingston, 2014). The internal bus bar and the terminals are made of tinned copper (Montanari et al., 2008) and welded onto the metal-end layers (Epcos, 2013). In the subsequent step, the capacitor elements are heated and dried to clear out moisture and avoid oxidation before they are packaged into the plastic frame and sealed with polyurethane resin (Epcos, 2013).

**Data collection**

All material constituents of the DC link capacitor except for the polyurethane resin are represented by suitable datasets in Ecoinvent 3. Hence, data for the fabrication of polyurethane potting resin used in capacitors was gathered separately from (Axson, 2013). The two constituents of the resin are polyol (77% of the mass) and methylene diphenyl di-isocyanate (23% of the mass), and both have matching datasets in the Ecoinvent 3 database (Weidema et al., 2013). They are mixed at room temperature and solidifies into a gel in 30 minutes after application. It then hardens over several days during the initial storage (Axson, 2013). A compilation of how the DC link capacitor constituents were matched with Ecoinvent 3 datasets (Weidema et al., 2013) is presented in Table 13.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>E3, aluminium, unspecified</td>
</tr>
<tr>
<td>Brass</td>
<td>E3, brass</td>
</tr>
<tr>
<td>Copper</td>
<td>E3, copper</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>E3, polycarbonate</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PET)</td>
<td>E3, polyethylene terephthalate, granulate, amorphous</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>E3, polypropylene, granulate</td>
</tr>
<tr>
<td>Polyurethane resin</td>
<td>E3, methylene diphenyl diisocyanate</td>
</tr>
<tr>
<td></td>
<td>E3, polyol</td>
</tr>
<tr>
<td>Tin</td>
<td>E3, tin</td>
</tr>
<tr>
<td>Zinc</td>
<td>E3, zinc</td>
</tr>
</tbody>
</table>

**Table 13: The matching of the material constituents in the DC link capacitor with datasets in Ecoinvent database version 3 (Weidema et al., 2013).**

Subsequently, it was identified that the Ecoinvent 3 activity “capacitor production, auxiliaries and energy use” (Hischier et al., 2007; Weidema et al., 2013) provides average data for all productions steps presented in the general section above. Although old (collected 1998-2005), it was still found representative for the DC link film capacitor manufacturing and judged as the currently best available data. A conceptual illustration for the LCI model use of this production activity is shown in Figure 16, referring to the individual material constituents provided in Table 13.

This activity only represents the use energy and auxiliaries of the manufacturing procedure. It does not include the material input to the capacitor. Hence, it can be regarded as product forming activity, similar to the reworking and forming activities for metals, plastic and elastomers (see sections 5.2.1, 5.2.2, and 5.3.1-5.3.3) existing in the Ecoinvent 3 database (Weidema et al., 2013), and described by Steiner and Frischknecht (2007) and Classen et al. (2009). As explained in Section 2.3, production efforts of this type have been included within the so called extended system boundary of the model and they are specified per the amount of material being processed, but do not include the material itself.
5.1.3 Production and assembly of printed circuits boards

The most common type of printed circuit boards (PCBs), classified as FR-4\textsuperscript{27}, are constructed with substrates of woven fiberglass cloths impregnated with an epoxy resin (Coombs, 2008). The substrate is cured and a pattern of copper conductors are built onto one or both sides of the substrate, either in a subtractive or an additive process. In the subtractive process, the substrate is laminated with a copper foil from which the pattern is formed. There are many steps in this process, including imaging the desired conduction pattern with photoresist and UV light, and stripping and etching with different chemicals (Willis, 2003, Coombs, 2008). In the additive method, the pattern is plated onto the substrate (Coombs, 2008). Several patterned substrates are joined into multiple layered boards by pressing them together in a second heat and pressure lamination step. It is a sandwich construction where each layer is bonded to the next layer with added pre-impregnated substrates\textsuperscript{28}, which are fully cured during the subsequent lamination (Willis, 2003, Coombs, 2008, LPKF, 2016). A patterned substrate layer is often referred to as a laminate. Copper surfaces are prepared with an oxidizing agent and oven baked before the bonding process (Coombs, 2008). Holes are drilled and trimmed, both in individual laminates and thought the multilayered board, and plated with copper to provide conduction routes between layers. Larger plated holes enable through-hole mounting, by soldering or press fitting, for example connectors and power module pin terminals. Holes are also used for tooling and aligning layers during manufacturing (Willis, 2003). The outer copper patterns are made last, often in a new series of subtractive processes, before the solder mask is applied by coating and curing, to protect the board from short circuits by improper soldering and for general environmental protection.

The components to be mounted on PCBs are of two types: active (integrated circuits, transistors and diodes) or passive (resistors, capacitors, inductors, transformers and connectors). Active components are made with doped silicon chips, in the same way as described in Section 5.1.1. However, surface mount devices (SMDs) are miniaturized parts and weigh only parts of a gram down to a few milligrams, for the complete package. The die (see Section 5.1.1) is glued to a metal leadframe which includes the legs of the component. The frame is typically made of copper (Coombs, 2008). The die and leadframe are bonded with a wire, e.g. made of gold, and molded into a plastic body (Coombs, 2008). Common passive SMDs, i.e. resistors and capacitors, are typically made of ceramic materials with metal end-faces and terminals, often copper with nickel or tin plating (Panasonic, 2008, TDK, 2010). However, film capacitors and aluminum electrolytic capacitors can also be made as SDMs, using the same production steps as for larger power capacitors, i.e. as described in Section 5.1.2 for film capacitors. For the latter type, aluminum foil layers are rolled with paper into a cylinder which is impregnated with electrolyte and packaged in an aluminum can (IC, 2011). Inductors and transformers are components comprising coils. Lacquered copper wire has been wound around an iron based core, and mounted with tin or nickel plated legs, sometimes in a molded plastic casing (Würth Elektronik, 2014, Epcos, 2016). Common for all types of SMDs is that they are stored and mounted from a

\textsuperscript{27} FR in the classification name stands for "flame retardant" or "flame resistant", indicating that there are additives included in the resin providing this functionality. PCBs in FR-4 group vary depending on the type of epoxy resin used and the selection of flame retardant.

\textsuperscript{28} "Prepregs" are fiberglass cloths which have been impregnated with epoxy resin and cured to an intermediate stage.
carrier tape which in turn is wound on a reel. Reels and tapes are often made of cardboard paper or plastics, and one reel can hold 3000-5000 components (Topline, 2016).

Unmounted PCBs are delivered to assembly factory as large panels. They are either pre-routed, and can then be easily separated by hand, or sawed into the selected board size. In preparation for surface mounting of components, it is wiped clean and placed in a stencil printing machine where solder paste is applied to the board. Solder paste is a mixture of solder metal alloy powder and “flux” with rheological characteristics suitable for printing. The role of the flux is to remove tarnish and oxidation on the solderable surface of the board and the solder itself (Coombs, 2008). Flux may have many compositions, but common main ingredients are alcohols and natural rosins (Coombs, 2008). Alcohols evaporate during the soldering process and the rosin may either stay on the board or evaporate. For some flux types, rosin residues have to be cleaned off after the soldering process, mainly to avoid corrosion, but for “no-clean” flux this is generally not necessary. There are many lead-free solder alloy options, consisting of tin with varying shares of silver (1-5%) and copper (0-1%) (Coombs, 2008). Bismuth is also a possible constituent.

The stencil acts as a template to make sure that the paste is applied in accordance with the dedicated PCB design, on the pads of the board where the solder joints shall bond the components. The stencil thickness is often 100-120 µm (Edgren, 2015). 90-100% of the pad area is matched by the stencil apertures (Deubzer, 2007), and the pad area constitutes about 30% of the board area, for an ordinary component density, such as in consumer electronics (Deubzer, 2007). On PCBs with very high component density, up to 50% of the board surface can be pad area (Deubzer, 2007), whereas on low density PCBs, for example in automotive applications with stricter thermal requirements, the pad area range between 5-20% (Edgren, 2015). Compared to through-hole technology, surface mounting allows for much higher component density at the same time as the solder consumption for equal package sizes is about 80% lower (Deubzer, 2007). Hence, surface mount technology is much more material efficient, both in terms of board area and the amount of solder used per PCB area unit.

Additionally, reflow soldering have lower solder losses than wave soldering. They mainly occur in the stencil printing process and through disposal of degraded paste (Edgren, 2015). The rate of loss in the printing is defined by the transfer efficiency, and it ranges from 1% to 3% (Amalu et al., 2011). The total loss rate for paste is higher, 5-15%, according to Deubzer (2007) and occasionally up to 20% according to Edgren (2015). In comparison, in wave soldering, 25-50% of the solder bar goes to waste (Deubzer, 2007). The main reason is dross formation, i.e. the molten solder oxidizes in contact with air. Dross must be removed regularly from the wave soldering process. On the other hand, waste solder is at least partly recycled, with expected global recovery rates of in the range of 50-60% (Deubzer, 2007).

The stencil printing procedure is sufficiently precise and clean to circumvent any cleaning of the board before it is shipped further to the pick and place machine. However, the stencil itself must be cleaned three to four times per day in an ultrasonic based washing machine, using water based “micro phase” washing liquids. Alkoxy propanols are the main ingredients in these fluids (Wypych, 2014). Solder frames are also washed, in a similar process. Removed dirt is caught in a filter and the solution is circulated to be re-used in many cleaning cycles (MBtech, 2007). As regards cleaning, these are the main steps in the surface mounting production line, complemented only by general manual cleaning of the machinery and PCBs.

Next, the pick-and-place machine locate the small SMDs precisely on the solder paste deposits and the populated PCB enters into the reflow oven to melt the solder. A pick and place machine can mount up to 60 000 components of 120 different types, per hour, as an example (ASM, 2012). Reflowing of lead free solder is conducted in a nitrogen cover gas atmosphere, in order to limit the oxidation of the tin and improve the surface wetting (Sheng and Colino, 2005, Coombs, 2008). The maximum temperature during the reflow cycle is set to 240-260°C (Coombs, 2008). After reflow, the board passes onto visual inspection and in circuit testing. There are conveyors moving the board from each machine to the next in a fully automated procedure.

At this stage, some PCBs may be subject to conformal coating. A layer of lacquer is applied on the board to protect it from moisture, salt, dirt, fungus and other contaminants. It also provides resistance to mechanical shock and vibration. Conformal coating is applied by spraying or dipping and it becomes thin enough for the coating to conform to shape of components and other features (Coombs, 2008). For automotive boards, the inclusion and selection of conformal coating material is a prioritization between requirements. Silicone coating is around 500 µm thick and applied when operating temperatures often go above 140°C (Edgren, 2017). Polyurethane lacquer has a dry thickness of 20-50 µm and is much less costly, but requires the use of solvents

---

29 In through-hole technology (THT) the leads of the components are inserted into holes in the PCB and soldered into place on the opposite side of the board, typically using wave soldering.

30 In wave soldering the PCB is carried on a conveyor belt through flux application and then over a pumped wave of molten solder.
Figure 17: The process flow for driver and logic board surface mount assembly.

as well as a 15-20 minute drying and hardening oven procedure at 80ºC (Peters, 2015, Edgren, 2017). For further vibration protection, the use of silicon potting gel on the PCB is an additional option (Edgren, 2017).

The complete PCB assembly procedure has been summarized in Figure 17, including the application of a conformal lacquer layer requiring drying and hardening.

Data collection

Data for the PCB assembly was gathered from Aros Electronics AB: through site visits; from electricity, purchase and waste data compilations (Aros, 2013, 2014a, c, d, e, f, g); and through interviews (Edgren, 2014, 2015, 2017). This data was complemented by machine and process chemicals specifications. The company documentation received extends back to 2007, but the main compilation considers the production during 2013. The starting point for the inventory are the datasets for unmounted lead free printed circuits boards and SMD component types in Ecoinvent version 3 (Weidema et al., 2013), as presented in sections 4.1.4 and 4.1.5. These datasets include the production of both components and the six layered FR-4 PCBs, as described in the technical background, previously in this section. Based on the reference design of the inverter unit driver board and logic board, the assembly line data compilation only covers surface mounting technology. The large external connector on the logic board, which is not included in the surface mounting procedure, was assumed to be mounted with selective soldering, during a later step in assembly of the PCB, and further described in Section 5.6.1.

The total amount of unmounted PCB panel area entering the assembly lines per year was calculated to 5900 m², based on purchase data (Aros, 2014f). This input of panel corresponds to 272 000 assembled circuit boards delivered to customers (Aros, 2014e). Losses of solder paste in the stencil printing and cleaning step was estimated to 10%, based on information from Edgren (2015), and in line with the background description.
An exact figure for solder paste loss was not attainable since disposed solder paste is mixed with dross and waste from the other soldering application procedures (Aros, 2014a), and registered as an aggregated amount of waste. However, waste free from lead is never mixed with waste containing lead. Also, based on the generic data for transfer efficiency, 30% of these losses (3% of the total use) was assumed to be caught in the cleaning filters. The remaining share of lost solder paste goes to waste handling as disposed solder.

The production procedures Aros Electronics AB include through-hole mounting as well as surface mounting, and convection reflow soldering, wave soldering, selective soldering and soldering by hand, with both leaded and lead free solder. The number of assembled PCBs which are lead free and RoHS compliant was well documented. It was also possible to acquire good estimates for the portion of all boards passing through different segments and stations of the assembly lines, including the different soldering ovens (Edgren, 2014). These estimates were then used recalculate and relate all compiled data to assembled square meter of board area. Losses of unmounted panel, components and assembled boards are generally very low, and Aros continuously strive to keep the total amount of such losses under 0.1% (Edgren, 2014). Hence, for components and solder on assembled boards, i.e. the waste flows from the surface component placement stage and the inspection and test stage in the process flow shown in Figure 17, losses were neglected. However, the loss was included in calculations of the board area subject to different process steps, but it was found to have a negligible influence on results.

The electricity use assessment has been summarized in Table 14, arranged in accordance with the process steps shown in Figure 17, and presented per square meter of board area. The component pick and place machine was found to use a very small amount of electricity for operation, about 0.02 mWh per component placed. Hence, was neglected in the summary. On the other hand, it was found to be the largest consumer of compressed air among all machines. This is further discussed in Section 5.6.2.

It should be noted that the throughput of board area is different for the steps presented in Table 14. This is particularly important for the drying and hardening of the conformal coating, since this oven has the same yearly operating time as two reflow ovens, but only one third of their throughput. Similarly, the hardening oven has the same size of the ventilation hood and the exhaust flow rate as the reflow ovens.

All ovens, including the wave soldering stations and the selective soldering machine are connected to a cooling system. One compressor drives the system, which also includes general cooling of the factory building. However, for the ovens, the temperature cycles and peak temperatures differ if the soldering is lead free or with lead. The total operating time per year also differs. The wave soldering ovens are not shut down when the factory is closed, while the other ovens operate during the shifts. Hence, in order to split the electricity consumption of the cooling compressor between the ovens (for the general cooling, see Section 5.6.1), a simple

<table>
<thead>
<tr>
<th>Process step</th>
<th>Energy per m²</th>
<th>Data collection method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stencil printing and cleaning</td>
<td>2.1 kWh</td>
<td>Machine power rating and operating time</td>
</tr>
<tr>
<td>Reflow oven, heating</td>
<td>17 kWh</td>
<td>Measurement</td>
</tr>
<tr>
<td>Reflow oven, ventilation</td>
<td>4.3 kWh</td>
<td>Calculated from plant data, one exhaust hood per large oven</td>
</tr>
<tr>
<td>Reflow oven, cooling</td>
<td>3.1 kWh</td>
<td>Plant data, allocated – operating time and maximum temperature</td>
</tr>
<tr>
<td>In-circuit test and inspection</td>
<td>1.7 kWh</td>
<td>Machine power rating and operating time</td>
</tr>
<tr>
<td>Spray coating</td>
<td>1.0 kWh</td>
<td>Machine power rating and average time per board</td>
</tr>
<tr>
<td>Hardening oven, heating</td>
<td>8.1 kWh</td>
<td>Scaled reflow oven data, based on maximum operating temperatures</td>
</tr>
<tr>
<td>Hardening oven, ventilation</td>
<td>6.4 kWh</td>
<td>Calculated from plant data, one exhaust hood per large oven</td>
</tr>
<tr>
<td>Hardening oven, cooling</td>
<td>1.5 kWh</td>
<td>Plant data, allocated – operating time and maximum temperature</td>
</tr>
<tr>
<td>Conveyors</td>
<td>0.7 kWh</td>
<td>Average machine power rating and operating time</td>
</tr>
</tbody>
</table>

Table 14: Electricity use in the assembly of lead free printed circuit boards, per process step. Each value is dependent on the throughput of board area which varies between the process steps.

31 EU legislation restricting the use of hazardous substances in electrical and electronic equipment.
allocation procedure was established. Allocation factors were calculated by multiplying each peak oven operating temperature with the number of weekly operating hours and the share of different solder types (lead or lead free) during 2013. Typical peak operating temperatures for the different oven types were gathered from Coombs (2008) and IPC (2016), for the soldering ovens, and (Peters, 2016), for the hardening oven. For the wave and selective soldering stations, the solder pot temperature was used.

Moreover, all machines in the PCB assembly lines at Aros, except for the reflow ovens and the hardening oven, are powered with pneumatics, i.e., compressed air. The pick and place machines consumes most, but overall is the consumption of pressurized air distributed evenly among the machines. Pneumatics are energy demanding, since relatively short active operations carry a load of losses from compressor heat and air leakage (Nordelöf et al., 2017, U.S. Department of Energy, 2003). Hence, a large share of the compressor energy goes to upholding the system pressure, also during standby (Nordelöf et al., 2017). As a consequence, the electricity consumption for compressed air is assessed as a part of building services, in Section 5.6.2.

Next, for the amount of solder applied on the driver and logic boards, it was assumed that the accumulated area of the pads on reference boards corresponds to 20% of the total board area, in line with expected component densities on PCBs for automotive applications, but at the high end (Edgren, 2015). Furthermore, it was assumed that 100% of this pad area is printed with paste and that the stencil thickness is 100 µm. In the LCI model, the solder paste was matched with the Ecoinvent 3 dataset for "solder, paste, Sn95.5Ag3.9Cu0.6, for electronics industry". This solder alloy consist of 95.5% tin, 3.9% silver and 0.6% copper. In turn, the solder alloy powder make up 89% of the paste mass and the remaining 11% is flux (Hischier et al., 2007). In solid form, this specific alloy mix has a density of 7350 kg/m³ (Geibig and Socolof, 2005). The no-clean flux in the solder paste used at Aros consist of about 45% denatured alcohol and 55% natural rosin, according to Koki (2006b). It has a marginally different composition to the solder paste included in Ecoinvent, so the flux data was judged relevant. The density of this flux in liquid form was calculated to about 940 kg/m³ (ScienceLab, 2013a, c). In turn, using the presented composition data and the densities of the constituents, it was possible to calculate the density of the Sn95.5Ag3.9Cu0.6 paste to 4210 kg/m³, using the “Greely formula”, as described by the Indium Corporation (2012).

The total paste use per square meter, including losses, was calculated to 94 g/m² and the actual amount of paste applied on the board, after printing but before reflow, was found to be 84 g/m². It was assumed that all flux evaporates, either as ethanol (the alcohol portion) or VOCs (the rosin portion). Hence, after reflow, the mass of the remaining solder on the board is 75 g/m² and in total 1.6 grams for the two reference boards, with 1.1 grams on the driver board and 0.5 grams on the logic board (0.1 dm², the area required by the external board connector, was excluded from the average solder paste application).

Notably, the actual solder paste consumption at Aros Electronics AB was not used to estimate the amount of paste used for the driver and logic boards. The reason was that it correlates with the type of application and the component density of the layout design, which is subject to large variation. Also, different mounting techniques and soldering options can be combined on the same board, and there was not sufficient data available to determine an average component density for SMDs compared to through-hole mounted components, despite that data for components and total board area was available, on an aggregated level.

Values for all cleaning processes was calculated from Aros purchase data (Aros, 2014e, g), combined with information from the washing liquid datasheets (Zestron, 2011a, 2003, 2011b). Filters and washing liquids are replaced at the same time, ranging from once every month to once every three months, and disposed as hazardous waste in the form of contaminated filter material and water based solvents. It was found that the ultrasonic cleaning processes consumes 65 g of alkoxy propanols, 10 g of amino alcohols and 320 g of deionized water per square meter of board area (Zestron, 2011a, b) (Wypych, 2014). The two washing liquid constituents was proxied to simple compounds of each type, dimethyl glycol monomethyl ether and ethanolamine, for the link to Ecoinvent 3 datasets (Weidema et al., 2013). All water is deionized from tap water on-site, and no process water is flushed as wastewater. Aros data for water use and general cleaning is further discussed in Section 5.6.2.

The conformal coating is sprayed onto the PCB with very precise control, on selected areas and with uniform coating. The process does not require masking or sealing. It was assumed that the driver and logic boards are sprayed on both sides with a polyurethane based lacquer. A wet thickness coating layer of 135 µm was assumed (Edgren, 2017), and this is sufficiently thin to enable spray coating on both sides of the board without the risk of dripping problems when the board is turned. The conformal coating resin has a solid mass

---

32 It is a Sn96.5Ag3.0Cu0.5 paste with 11.5% flux (more natural rosin). The alloy density is 7320 kg/m³ and the paste density is 4130 kg/m³ (Koki, 2006a).
33 Volatile organic compounds, a group name for substances with common environmental and health effects.
share of 39% (Peters, 2016). Aros purchase data indicated that the polyurethane resin is diluted with 10% thinner to get proper viscosity for the spray operation (Aros, 2014g, Peters, 2014). The solvent share of the conformal coating resin consist of mainly an isoparaffinic hydrocarbon fluid (Peters, 2008), with a density of 748 kg/m³ (Brenntag Solvents, 2008). The densities of the coating resin and the recommended thinner was noted to be 860 kg/m³ (Peters, 2016) and 860 kg/m³ (Peters, 2014), respectively.

Combining all this data it was possible to derive that the dry coating layer is 40 µm and weighs 41 g/m² of spray coated board area. This resulted in a modest 1.2 grams of lacquer on the driver board and 0.6 grams on the logic board, taking both sides into account. The solid mass for this type of resin is built by two ingredients according to Dow Chemicals (Li et al., 2015), 15% poly-aldehydes and 85% poly-carbamates. The two constituents were proxied with “benzaldehyde” and “carbamate compound” in Ecoinvent 3 database (Weidema et al., 2013). The total wet mass came to 116 g/m², counting spray coated area, with 12 g/m² thinner in form of butyl acetate (available in Ecoinvent) and 63 g/m² resin solvent proxied as the “isohexane” dataset (Weidema et al., 2013). Both solvents have been assumed to be released as 100% VOC.

Finally, the use of nitrogen as cover gas in the reflow oven and in the spray coating was calculated based on information from (Edgren, 2015) the nitrogen flow rate setting on different machines and Aros total consumption of nitrogen per year (Aros, 2014d). The total use for the two steps was found to be 64 kg/m², whereof spray coating represent only a minor share with 0.5 kg per square meter of board area, when both sides are coated. The result of the data compilation is presented Table 15 and Table 16.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>46 kWh</td>
<td>1.02 kWh</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Cleaning liquid, alkoxypropanol</td>
<td>65 g</td>
<td>1.4 g</td>
<td>Multiple, see text. E3, dipropylene glycol monomethyl ether</td>
</tr>
<tr>
<td>Cleaning liquid, amino alcohol</td>
<td>10 g</td>
<td>0.2 g</td>
<td>Multiple, see text. E3, monoethanolamine</td>
</tr>
<tr>
<td>Cleaning liquid, deionized water</td>
<td>320 g</td>
<td>7.1 g</td>
<td>Multiple, see text. E3, water, deionised, from tap water, at user</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>64 kg</td>
<td>1.4 kg</td>
<td>(Aros, 2014d) E3, nitrogen, liquid</td>
</tr>
<tr>
<td>Solder paste, lead-free</td>
<td>94 g</td>
<td>2.0 g</td>
<td>Multiple, see text. E3, solder, paste, Sn95.5Ag3.9Cu0.6</td>
</tr>
<tr>
<td>Conformal coating, isoparaffin</td>
<td>126 g</td>
<td>3 g</td>
<td>Multiple, see text. E3, isohexane</td>
</tr>
<tr>
<td>Conformal coating, polyaldehyde</td>
<td>12 g</td>
<td>0.3 g</td>
<td>Multiple, see text. E3, benzaldehyde</td>
</tr>
<tr>
<td>Conformal coating, polyaldehyd</td>
<td>70 g</td>
<td>1.5 g</td>
<td>Multiple, see text. E3, carbamate compound</td>
</tr>
<tr>
<td>Conformal coating, thinner</td>
<td>24 g</td>
<td>0.5 g</td>
<td>Multiple, see text. E3, butyl acetate</td>
</tr>
</tbody>
</table>

Table 15: Process input for the assembly of 1 m² surface mounted printed circuit boards for automotive applications. Conformal coating has been applied on both sides of the board. The column for “Ref. PCBs” provides the summed result for the assembly of the driver and logic boards. Surface mounted devices and unmounted boards are excluded.

<table>
<thead>
<tr>
<th>Waste</th>
<th>Amount</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disposed cleaning liquid, conc. share</td>
<td>75 g</td>
<td>1.6 g</td>
<td>Multiple, see text. E3, spent solvent mixture</td>
</tr>
<tr>
<td>Filter waste</td>
<td>3 g</td>
<td>60 mg</td>
<td>Multiple, see text. E3, hazardous waste, for incineration</td>
</tr>
<tr>
<td>Solder paste waste</td>
<td>7 g</td>
<td>140 mg</td>
<td>Multiple, see text. Solder waste, optional recycling</td>
</tr>
</tbody>
</table>

Table 16: Waste and emissions to air from the assembly of 1 m² surface mounted printed circuit boards for automotive applications. Conformal coating has been applied on both sides of the board. The column for “Ref. PCBs” provides the summed result for the assembly of the driver and logic boards. Surface mounted devices and unmounted boards are excluded.
5.2 Manufacturing of copper, brass and steel subparts

5.2.1 General processing of copper and brass parts

There are several subparts of the inverter unit which are formed and machined from slabs of pure copper, and then continue to coating and integration in larger subcomponents. The power module includes thin copper foils in the DCB (direct copper bonded substrate), the baseplate, the contacts for the power terminals, pin terminals and the bonding wire. Shaped and bent copper bars and plates also make up most of the mass in laminated bus bars.

Foils, plates and bars are made from coiled copper sheets of various thickness and width which are machined into the desired shape by cutting, punching or drilling. Sheet making involves hot rolling and cold rolling (Classen et al., 2009). The two processes involve several steps where heating, rolling between large rolls and chemical and mechanical surface treatments are combined and repeated in different setups, which finally result in the hardened metal sheet (Classen et al., 2009). The sheet thickness is decided by the number of stepwise cold rolling operations.

Copper wire production starts with the making of a wire rod by rolling in a process similar to the sheet rolling, followed by cutting. The rod is then repeatedly pulled through drawing dies to reduce the cross section into a wire of a desired size (Classen et al., 2009). Slightly thicker elongated objects, such as pins, can also be made from rods which are cut and formed by various machining steps.

Brass cable glands can be made both by casting and extruding the brass alloy (CMP, 2015). In the following step they are machined to their final shape including threads.

Data collection

All making of copper and brass parts in the inverter unit has been modeled with metal working and forming activities existing in the Ecoinvent 3 database (Weidema et al., 2013), as described by Steiner and Frischknecht (2007) and Classen et al. (2009). As explained in Section 2.3, production activities of this type have been included within the so called extended system boundary of the LCI model. These datasets do not include the metal ending up in the inverter unit subcomponents. Instead they account for the material losses, energy use and other process inputs and outputs during the material handling and part fabrication. The activities covering specific machining steps, such as turning, are referenced to the amount of metal removed, and not the amount remaining in the resulting part (Steiner and Frischknecht, 2007).

The Ecoinvent 3 activities selected to model general processing of copper parts are shown in Figure 18. “Wire drawing, copper” was chosen for the making of the pure copper wire. This activity includes both rolling of copper into rods and further drawing into wire. Foils, plates and bars were modeled to go through “sheet rolling, copper” and “metal working, average for copper product manufacturing” to cover for sheet making (assuming that the modelled thickness is representative, on average, for all different sheets) and for cutting. Likewise, the rolling of cylindrical thin rods to make contact pins was approximated with the “sheet rolling, copper” activity, and the final machining step by “metal working, average for copper product manufacturing”.

![Figure 18: Production activities for copper available in Ecoinvent 3 (Weidema et al., 2013), specified per kilogram of material being processed. These processes have been included within the extended system boundary of the LCI model, to account for general processing of copper parts.](image-url)
Figure 19: Production activities for brass available in Ecoinvent 3 (Weidema et al., 2013), specified per kilogram of material being processed (for the casting step) or the amount of material being removed (the turning step). These processes have been included within the extended system boundary of the LCI model, to account for the tin plating of copper lugs.

Figure 19 shows the Ecoinvent 3 activities (Weidema et al., 2013) selected to represent the production of the brass glands. It was assumed that the brass parts are first casted and then machined into their final shape by computer controlled turning, i.e. activities “casting, brass” and “brass turning, average, computer numerical controlled” were selected. No information was found for how much excess material a typical casting process would yield. Instead, an average value was used, 0.23 kg metal removed per kg metal being processed, as recommended in the Ecoinvent 3 database (Steiner and Frischknecht, 2007, Weidema et al., 2013).

5.2.2 Production efforts for steel parts

Hot rolling is an intermediate steel making process where the ingots, blocks, and beams from raw steel making are treated to receive enhanced durability, shock resistance and tensile strength. The incoming alloy is heat treated and rolled into long or flat products. Terminals, screws and washers are made from a bar which is reheated, rolled again and mechanically machined to proper dimensions. Round or hexagonal carbon steel rods are forged, threaded and cut, or cut and drilled to become screws and washers which are cleaned and coated with zinc in a galvanizing procedure (see Section 5.2.3). The environmental burden of rolling mainly derives from emissions to air of nitrogen oxides, sulfur oxides and dust, along with the energy consumption and oil containing wastes (Classen et al., 2009).

Data collection

The making of steel parts used in the inverter unit was modeled starting from the dataset for “steel, low-alloyed” and supplemented with recommended metal working and forming activities, all existing in the Ecoinvent 3 database (Weidema et al., 2013). Figure 20 shows an overview of the Ecoinvent 3 production activities, recommended to account for manufacturing steel parts. Production efforts of this type have been included within the extended system boundary of LCI model, see Section 2.3, since they do not incorporate flows of material ending up in the final product, but they are specified per the amount of material being processed (Steiner and Frischknecht, 2007, Classen et al., 2009). Hot rolling was applied in the first step. There are no losses in this activity dataset, and the underlying assumption is that any scrap is recycled back to alloying plant from the rolling mill without net material losses. Section bar rolling and average machine processing take losses into account within the activity (Steiner and Frischknecht, 2007, Classen et al., 2009).

Figure 20: Production activities for steel available in Ecoinvent 3 (Weidema et al., 2013), specified per kilogram of material being processed. The processes have been included within the extended system boundary of the LCI model, to account for general processing of steel parts.
5.2.3 Electroplating of metal surfaces

Coating of nickel on copper, for example in the foils of the DCB (direct copper bonded substrate), the baseplate and the auxiliary pin terminals, in the power module, can be achieved in a process called electroplating, i.e. plating based on the use of electricity and an electrolyte bath of metal salts (Moing et al., 2009, Schlesinger and Paunovic, 2010). The same technique can also be applied to plate gold over nickel, nickel on brass and for electro-galvanization, i.e. zinc coating of the steel (Schlesinger and Paunovic, 2010). Electro-galvanization is used for coating thicknesses up to 20 µm (Walraven, 2011). In brief, all surfaces have to be cleaned, first in an alkaline solution to remove grease and then in an acid solution to remove oxides, called activation (Moing et al., 2009, Schlesinger and Paunovic, 2010). The last step of the cleaning is rinsing in pure water. It is also used to rinse the surface after plating. The most common alkali cleaner is caustic soda (sodium hydroxide), but other sodium based substances such as sodium carbonate and sodium phosphate are also used (Schlesinger and Paunovic, 2010). Electrolytic activation in sulfuric acid, i.e. cleaning with support of an electric current, is used for copper and steel surfaces for high precision (Schlesinger and Paunovic, 2010). When gold is plated on nickel, activation is important as the nickel otherwise might peel off. It can be conducted by dipping the part in a hydrogen chloride bath (Schlesinger and Paunovic, 2010).

The deposition of metal coating on a surface is directly proportional to the quantity of electricity used, prescribed by Faraday’s law for electrolysis (Schlesinger and Paunovic, 2010). It states that:

\[
\text{Deposed mass} = \frac{\text{Molar mass}}{\text{Oxidation state} \times \text{Faraday’s constant}} \times \text{Bath efficiency} \times \text{Current} \times \text{Time} \quad \text{(Eq. 14)}
\]

By introducing the DC voltage used, it can be rewritten to:

\[
\text{Electric energy} = \frac{\text{Oxidation state} \times \text{Faraday’s constant} \times \text{Voltage}}{\text{Molar mass} \times \text{Bath efficiency}} \times \text{Deposited mass} \quad \text{(Eq. 15)}
\]

As shown, the molar mass\(^{34}\) and the oxidation state of the metal ion matter for the electricity consumption. The oxidation state of the metal ion is the same as the number of electrons taking part in the reaction per atom of the element (Schlesinger and Paunovic, 2010). Nickel and zinc primarily react in the two (+2) state, and gold in the one (+1) or three (+3) states, with the +1 state as the most common for electroplating (Schlesinger and Paunovic, 2010). Faraday’s constant expressed in ampere hours is 26.8 Ah/mole (Schlesinger and Paunovic, 2010).

Bath efficiencies around 95% are reasonable and common, although much lower efficiencies also occur (Schlesinger and Paunovic, 2010). A metal source is functioning as the anode, supplying material to deposit on the cathode side. The anode can be made of pure metal, a plated metal or an alloy, depending on the bath. The lack of a 100% efficiency implies that there is a loss of plating metal to the residue bath. Likewise, all rinsing steps can be expected to cause “drag-out” losses of chemicals to the disposed rinsing water (Moing et al., 2009). Baths solutions for functional plating are often based on nickel sulfamate for nickel and cyanide-based for gold (Schlesinger and Paunovic, 2010). In the case of electro-galvanization, zinc in solution with acid chloride is common (Schlesinger and Paunovic, 2010).

Water in solution baths and used for rinsing can be of different quality. In general, for electronics production, it is common to use water with higher purity than tap water, typically deionized water or even further ultra-filtrated water (Sheng and Colino, 2005, Hutcheson, 2006).

Finally, as pointed out in section 4.1.2, a typical nickel layer thickness on the baseplate is 3-10 µm. Terminals with double coating have thinner deposits, for example 1.5 µm of nickel, and 0.3 µm of gold (Volke and Hornkamp, 2012).

Data collection
As a general approach in the LCI model, the areas for cleaning and plating of the different copper, brass and steel substrates are calculated using the total mass of metal coating on the specified part, combined with the stated plating layer thicknesses and the densities. Nickel has been plated on the bus bar copper conductors with

\(^{34}\) For pure elements, the relative atomic mass is often tabulated. It relates to the molar mass through the molar mass constant \(M_u\), which is 1 g/mole in SI units.
a 20 µm coating layer (described in Section 4.2.5), and on the surface of the brass cable glands in a 7 µm coating layer (see Section 4.2.6). Steel screws and washers used in the inverter unit assembly have been electro-galvanized with a 15 µm coat of zinc. Remaining plating procedures involve subparts of the power module.

The nickel layer applied on the power module baseplate and foils was assumed to be 3 µm. This values is towards the thinner end of expected baseplate coating layers, but still in line with the general design principles. The geometries of the baseplates for the two reference power modules were measured, including holes for mounting various screws (Infineon, 2012a, 2014b). The surface area was calculated and combined with the area of for the foils, taken from the description of the DCB (see Section 5.5.2). The total amount of nickel in the module was divided into two portions, one of for the thicker plating layer on the foils and baseplate, and one for the coating applied on the auxiliary terminals. The coating thicknesses and the mass shares of the copper parts were used to establish calculation factors35 for the two nickel portions. 89% of the nickel mass was portioned to the plating of the foils and the baseplate. It showed to correspond well with the mass of a 3 µm thick coating layer for both reference modules. At the same time, the remaining 11% of the nickel mass was assumed to be plated on the auxiliary terminals, in a 1.5 µm layer under the final gold layer. In turn, starting over from the gold mass, it was found to yield a 0.5 µm gold layer on the same terminal area, for both reference modules. Finally, the zinc mass of the power module was used to calculate the area for a 15 µm galvanization layer on the steel parts. This area was also compared with screws and terminals in correct numbers and suitable sizes for the two reference units. Both masses and areas were found to match well with the LCI model calculation procedure.

Next, data for the cleaning of surfaces before electroplating was gathered from Moing et al. (2009), representing alkaline cleaning and electrolytic activation before nickel plating, but judged representative also for the cleaning of brass and steel. All the sodium salts (sodium carbonate, trisodium phosphate, sodium gluconate and caustic soda) were proxied as caustic soda, which is the largest constituent, for simplicity. Moing et al. (2009) present different figures for the use of rinsing water, one best and worst case. The best case, i.e. the lower water use, was selected to align with the data for bath efficiency for the plating step, explained further down. Table 17 presents a summary of the process inputs for cleaning of copper, brass and steel surfaces. The rinsing wastewater was not inventoried by Moing et al. (2009). However, here it was anticipated that all rinsing waste go through internal plant wastewater treatment, in a simplification recommended to be modelled as “wastewater, average” by linking to Ecoinvent wastewater treatment processes (Weidema et al., 2013), see Table 18.

For the gold deposed over nickel, data was gathered for a new activation step, following directly after the nickel plating, in a hydrochloric acid solution, with 50% concentration by volume (Schlesinger and Paunovic, 2010). Table 19 was established by recalculating the hydrochloric acid volume share to mass per liter (LabChem, 2013), and combining this data with the amount of solution used per square meter of surface area and total amount of water used, including rinsing, (Moing et al., 2009). Table 20 provides the liquid waste.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.42 kWh</td>
<td>Moing et al. (2009)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Caustic soda</td>
<td>10 g</td>
<td>E3, sodium hydroxide, without water</td>
<td></td>
</tr>
<tr>
<td>Sulfuric acid</td>
<td>18 g</td>
<td>E3, sulfuric acid</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>16 kg</td>
<td>E3, water, deionised, from tap water, at user</td>
<td></td>
</tr>
</tbody>
</table>

Table 17: Process input for cleaning of 1 m² of metal surface before electroplating.

<table>
<thead>
<tr>
<th>Liquid waste</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater</td>
<td>16 dm³</td>
<td>Matching rinsing water</td>
<td>E3, wastewater, average</td>
</tr>
</tbody>
</table>

Table 18: Liquid waste for cleaning of 1 m² of metal surface before electroplating.

---

35 In Section 4.1.2, it is presented that around 80% of the copper mass in the power module resides in the foils and the baseplate, for both reference power modules. The DCB foils and baseplate surface areas were expected to be plated with 3 µm nickel. The remaining 20% copper in the power module make up terminals, internal bus bars and wire, whereof only the terminals were expected to be plated with 1.5 µm nickel. The copper mass shares and coating layer thicknesses were combined into calculation factors for the nickel mass: 89% and 11%.
ckel sulfamate, nickel chloride, for simplicity.

The plating facility. This loss of nickel, in the form of nickel sulfamate, is allowed to be emitted per liter of waste, and potassium hydroxide, but it also contains gold(I)potassium cyanide. Neither any restrictions for emissions to water, nor any emission factors for emissions to air were found for gold. Instead, for this type of bath, it is the cyanide which is the main pollutant. US federal regulations (US EPA, 2016) were used to quantify that at most 2.7 mg of cyanide is allowed to be emitted per liter of wastewater from the plating facility, as an average over a four day period (Schlesinger and Paunovic, 2010, US EPA, 2016). Airborne emissions of cyanide were estimated by

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrochloric acid</td>
<td>22 g</td>
<td>LabChem (2013), see text.</td>
<td>E3, hydrochloric acid, w/w, in 30% solution state</td>
</tr>
<tr>
<td>Water</td>
<td>8 kg</td>
<td>Moing et al. (2009)</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
</tbody>
</table>

Table 19: Process input for cleaning (activating) of 1 m² of nickel surface before gold electroplating.

<table>
<thead>
<tr>
<th>Liquid waste</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater</td>
<td>8 dm³</td>
<td>Matching rinsing water</td>
<td>E3, wastewater, average</td>
</tr>
</tbody>
</table>

Table 20: Liquid waste for cleaning (activating) of 1 m² of nickel surface before gold electroplating.

Subsequently, data was gathered for the plating steps of the three different coating metals. The dataset for nickel plating was collected in its entirety from Moing et al. (2009). A pure nickel anode provides the nickel being consumed and the surface to be plated acts as the cathode. To account for the thinner coating layer, the amount of electricity used was decreased proportionally with the mass, fully in line with Faraday’s law for electrolysis (Schlesinger and Paunovic, 2010). Moing et al. (2009) presented two cases for the bath efficiency. The best case, with a 95% efficiency was selected, as this was more in line with other references than the worst case (Schlesinger and Paunovic, 2010). The plating bath consists of nickel sulfamate, nickel chloride, boric acid and sodium saccharin. Most of the nickel lost as drag-out in rinsing was expected to be caught in internal waste treatment processes and fixed in the filter sludge. Nickel emissions to air were also included, originally deriving from the US EPA (1994, 1996), but still valid (US EPA, 2016). Similar to the cleaning steps, the local wastewater handling was modelled by referring to the in Ecoinvent 3 dataset “wastewater, average” (Weidema et al., 2013).

Over time, the electrolyte bath can be expected to require refill and exchange due to the drag-out losses during rinsing, losses to sludge formation and contamination. However, these effects are assumed to be both small and slow, and they were not included by Moing et al. (2009), for simplicity. Accordingly, to simplify more consistently, drag-out losses of boric acid and sodium salt were not included here. However, the data compilation includes the assumption for water emissions of nickel made by Moing et al. (2009). It was based on French regulations for electroplating which allows that at most 2 mg nickel per liter of wastewater continues through the wastewater treatment at the plating facility. This loss of nickel, in the form of nickel sulfamate, and the rinsing water use is proportional to the surface area being plated, as the cleaning steps. Wastewater was modelled as for the cleaning steps. Table 21 and Table 22 shows the data compilation for the nickel plating.

Data for electroplating gold over nickel was established using information from Schlesinger and Paunovic (2010) and US EPA (1996) to modify the nickel plating dataset provided by Moing et al. (2009). Acid cyanide baths provide the best results for connector plating and have very high efficiency, almost 100% (Schlesinger and Paunovic, 2010). Hence, the bath efficiency was set to 99%. Main ingredients of the bath are citric acid and potassium hydroxide, but it also contains gold(I)potassium cyanide. Neither any restrictions for emissions to water, nor any emission factors for emissions to air were found for gold. Instead, for this type of bath, it is the cyanide which is the main pollutant. US federal regulations were used to quantify that at most 2.7 mg of cyanide is allowed to be emitted per liter of wastewater from the plating facility, as an average over a four day period (Schlesinger and Paunovic, 2010, US EPA, 2016). Airborne emissions of cyanide were estimated by

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>1053 g</td>
<td>Calculated from bath efficiency.</td>
<td>E3, nickel, 99.5%</td>
</tr>
<tr>
<td>Electricity</td>
<td>4.8 kWh</td>
<td>Modified from Moing et al. (2009)</td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>

Table 21: Process input for electroplating nickel, given per 1 kg of nickel or per 1 m² of plated area depending on the input type.

<table>
<thead>
<tr>
<th>Emissions to air</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked elementary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
<td>42 mg</td>
<td>Moing et al. (2009)</td>
<td>E3, nickel, unspecified</td>
</tr>
<tr>
<td>Emissions to water</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked elementary flow</td>
</tr>
<tr>
<td>Nickel, in sulfamate¹</td>
<td>16 mg</td>
<td>Moing et al. (2009)</td>
<td>E3, nickel, ion²</td>
</tr>
<tr>
<td>Liquid waste</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Wastewater</td>
<td>8 dm³</td>
<td>Matching rinsing water</td>
<td>E3, wastewater, average</td>
</tr>
<tr>
<td>Solid waste</td>
<td>Amount per kg</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Sludge¹, dry content</td>
<td>53 g</td>
<td>Calculated from bath efficiency.</td>
<td>Hazardous waste, optional</td>
</tr>
</tbody>
</table>

**Note 1:** Nickel constitutes 23% of the mass in nickel sulfamate
**Note 2:** Relevant flow for the nickel share. It is assumed that the salt is fully dissolved.
**Note 3:** Nickel contribution to sludge caught in the filters of the local plant wastewater treatment system.

Table 22: Emissions and waste for electroplating nickel, given per 1 kg of nickel or per 1 m² of plated area depending on the emission or waste type.

Comparing the nickel emissions from a wet scrubber system (used by Moing et al.) with copper cyanide plating using a different end of pipe solution, a mesh pad mist eliminator (US EPA, 1996). The emission factor for cyanide was found to be about five times higher than that for nickel (US EPA, 1996). This was used to recalculate the data from Moing et al. (2009), taking also the plating efficiency and the molar mass into account.

The electricity use for gold plating was rescaled from the nickel dataset accounting for the difference in molar mass between nickel and gold, the increased bath efficiency and the change of oxidation number. The resulting gold electroplating dataset is presented in Table 23 and Table 24. As it can be noted, gold plating is energy efficient compared to nickel plating.

Finally, a similar approach was adopted to compile new data for electro-galvanization of steel. Again, data for the electricity use was rescaled from Moing et al. (2009), based on the molar mass difference. Zinc has the same oxidation number as for nickel. The bath efficiency was also assumed to 95%. A typical acid chloride bath for functional plating of zinc contain zinc in solution with ammonium chloride and a fatty alcohol brightener (Schlesinger and Paunovic, 2010). US federal regulations were used to quantify that at most

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gold</td>
<td>1010 g</td>
<td>Calculated from bath efficiency.</td>
<td>E3, gold</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.7 kWh</td>
<td>Calculated, see text.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Process input</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Water</td>
<td>8 kg</td>
<td>Moing et al. (2009)</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
</tbody>
</table>

Table 23: Process input for electroplating gold, given per 1 kg of gold or per 1 m² of plated area depending on the input type.

<table>
<thead>
<tr>
<th>Emissions to air</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked elementary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyanide</td>
<td>56 mg</td>
<td>US EPA (1996), see text.</td>
<td>E3, cyanide, unspecified</td>
</tr>
<tr>
<td>Emissions to water</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked elementary flow</td>
</tr>
<tr>
<td>Cyanide</td>
<td>22 mg</td>
<td>Schlesinger and Paunovic (2010)</td>
<td>E3, cyanide, unspecified</td>
</tr>
<tr>
<td>Liquid waste</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Wastewater</td>
<td>8 dm³</td>
<td>Matching rinsing water</td>
<td>E3, wastewater, average</td>
</tr>
<tr>
<td>Solid waste</td>
<td>Amount per kg</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Sludge¹, dry content</td>
<td>10 g</td>
<td>Calculated from bath efficiency.</td>
<td>Hazardous waste, optional</td>
</tr>
</tbody>
</table>

**Note 1:** Gold contribution to sludge caught in the filters of the local plant wastewater treatment system.

Table 24: Emissions and waste for electroplating gold, given per 1 kg of gold or per 1 m² of plated area depending on the emission or waste type.
<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per kg</th>
<th>Source for calculations:</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>1053 g</td>
<td>Calculated from bath efficiency.</td>
<td>E3, zinc</td>
</tr>
<tr>
<td>Electricity</td>
<td>4.3 kWh</td>
<td>Calculated, see text.</td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source for calculations:</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>8 kg</td>
<td>Moing et al. (2009)</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
</tbody>
</table>

Table 25: Process input for electro-galvanizing (zinc plating), given per 1 kg of zinc or per 1 m² of plated area depending on the input type.

<table>
<thead>
<tr>
<th>Emissions to water</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked elementary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc¹</td>
<td>21 mg</td>
<td>Schlesinger and Paunovic (2010)</td>
<td>E3, zinc, ion</td>
</tr>
<tr>
<td>Liquid waste</td>
<td>8 dm³</td>
<td>Matching rinsing water</td>
<td>E3, wastewater, average</td>
</tr>
<tr>
<td>Solid waste</td>
<td>53 g</td>
<td>Calculated from bath efficiency.</td>
<td>Hazardous waste, optional</td>
</tr>
</tbody>
</table>

Note 1: Dissolved in water with ammonium chloride.
Note 2: Zinc contribution to sludge caught in the filters of the local plant wastewater treatment system.

Table 26: Emissions and waste for electro-galvanizing (zinc plating), given per 1 kg of zinc or per 1 m² of plated area depending on the emission or waste type.

2.6 mg of zinc is allowed to be emitted per liter of wastewater from the plating facility, averaged over a four day period (Schlesinger and Paunovic, 2010). No data for airborne emissions of zinc was found, and consequently not included. The dataset for zinc plating is presented in Table 25 and Table 26.

5.3 Preparation of plastics and elastomers

5.3.1 Molded parts in the power module and glands

Three subparts in the inverter design are made of molded plastics: the power module frame and lid, and the lamellar inserts of the cable glands. Injection molding is a common but energy-intensive method to fabricate plastic shapes from granulates. The important process steps are melting, injection, cooling and shaping (Hirschier, 2007).

In the case of the power module frame and lid, the input thermoplastic material is polyphenylene sulfide (PPS) powder which is mixed with glass fiber and a small amount of diantimony trioxide. The plastic lamellar insert is made of nylon, also mixed with glass fiber.

Data collection

First, the ingredients of the molded parts were provided with recommended links to upstream data in Ecoinvent 3 (Weidema et al., 2013). In this procedure, diantimony trioxide was approximated with pure antimony metal, since the commercial production of the two related substances have most process steps in common (Grund et al., 2012). The other substances were found to have matching datasets.

Next, injection molded parts were modeled with Ecoinvent data for “injection moulding” (Weidema et al., 2013), see Figure 21. In line with the description in Section 2.3, this process was included within the extended system boundary of the model. Similar to the other material conversion processes of this type, it has the functional unit of one kilogram, but it does not include the material being processes. Confusingly, due to losses, reshaping one kilogram with this production activity yields 0.994 kg of molded product (Hirschier, 2007).
5.3.2 Extruded foils, spacers and rubber seals

Extrusion is another method for shaping plastics and elastomers (rubber-like materials), even more common than injection molding (Hischier, 2007). Plastic films and pipes of various thickness, hard and stiff, or soft and flexible, can be produced from granulates. This production method applies both bus bar insulation foils made of PET (polyethylene terephthalate), the hard nylon spacers and the soft silicone rubber o-rings and gland seals. Generally, most of the energy use in the procedure derives from the heat necessary to plasticize the granulates. In the case of silicone, it is extruded cold, i.e. below 20ºC. On the other hand it requires heat for the crosslinking process (Leoni, 2014), directly after the extrusion. This takes place in a special furnace where a crosslinking agent links the silicone molecules into a three-dimensional web.

**Data collection**

The preparation of small and thin extruded plastic and elastomer parts was modeled with ready-made Ecoinvent 3 activities (Weidema et al., 2013), in the same way as injection molded plastics, and copper, brass and steel parts, described earlier, within the extended system boundary. For further details, read Section 2.3. Two relevant extrusion activities for foils were found available in Ecoinvent, see Figure 22, one for general extrusion production of films and one for co-extrusion (multiple layers extruded at the same time). MYLAR foils can be both single layered or have co-extruded layers (Dupont, 2004). Hence, the newer of the two datasets was selected, “extrusion, co-extrusion of plastic sheets”. For the shaping of the cylindrical nylon and silicone parts, “extrusion, plastic pipes” was selected. Although silicone is extruded at low temperature, the subsequent crosslinking furnace process was assumed to balance up the lower heat use during the extrusion.

It should be noted that, due to losses, one kilogram of input yields 0.969 kg of sheet or 0.996 kg of ring or pipe shaped products, respectively, with these production activities (Hischier, 2007, Weidema et al., 2013).
5.3.3 Bus bar lamination process

Lamination refers to the manufacture of a product in multiple layers with the aim to achieve a composite product drawing the benefits of the different material properties of the different layers, i.e. strength, stability, insulation or conductivity (Storm, 2016). Laminated bus bars consist of layers with copper conductors and dielectric foils. Foils are cut to suitable size and heated before they are stacked up with the conductors and compressed when all layers have been set (Vanhoutte and Roelandt, 2009, Storm, 2016). The metal conductor has been cleaned and plated before the assembly (Vanhoutte and Roelandt, 2009). Foils are coated with an adhesive, for example an acrylic adhesive in the case of polyester foils, to provide proper bonding to the metal surface (Vanhoutte and Roelandt, 2009) The merged, single structure is inspected and, if necessary, adjusted to make sure that all surfaces are clean and even, and that the insulation is effective as intended.

Data collection

The Ecoinvent 3 database (Weidema et al., 2013) was found to provide a suitable dataset to represent the bus bar lamination process, “laminating service, foil, with acrylic binder”. This activity includes cutting and spray coating of the foils, and heating and pressing the laminate structure, by providing adhesive use and waste, and electricity use for cutting and laminating. Again, as the other Ecoinvent production activities (see sections 5.1.2, 5.2.1, 5.2.2, 5.3.1, 5.3.2), it is provided as a service specified per the amount of material being processed, but do not include the material itself. The input and output flow of this activity is defined by the amount of foil, expressed in square meters. This area is calculated in the LCI model, in an intermediate calculation step for the bus bar PET foil mass, as described in section 4.2.5. The activity was included within the extended system boundary of the model which is explained in Section 2.3.

![Figure 23: Production activity for lamination available in Ecoinvent 3 (Weidema et al., 2013), specified per square meter of foil being processed. The process has been included within the extended system boundary of the LCI model, to account for the final step in the manufacturing the laminated bus bar.](image)

5.4 Aluminum casing production

5.4.1 Overview

The process flow modeled for the aluminium casing manufacturing is shown above, in Figure 24. Both casing options have been supposed to be made by die casting. Extrusion is likely more common when making finned heat sinks used for air cooling, but casting was found more representative considering both heatsink types and especially the combination with the selected housing compartment design. Likewise, it is more common to anodize extruded parts than casted (Davis, 1993). However, anodizing castings is still an option (Davis, 1993). For the LCI-model as a whole, it was taken into consideration that liquid cooling is the default setting, and that air cooling only is an option for part of the model span.

Figure 24 shows that the casing is first casted in the “foundry” and then machined and coated in the “workshop”. This clearly defined split into two sections of the envisioned plant was made to clarify that the technical building services collected for and allocated to the casing production, further described in Section 5.6.2, only apply to the machining and coating steps, taking place in the workshop. The dataset for die casting described in Section 5.4.2 already comprise building services.
Figure 24: Overview of the aluminum casing fabrication as included in LCI model.

5.4.2 Die casting

Casting is a common method to produce aluminum shapes such as electric machine housing or casings for power electronics (Tong, 2014, Rose, 2016). Other competing methods can also be used, for example extruding, forging or stamping. The benefit of casting is that geometrically complex shapes can be produced with high efficiency and at low cost, especially in large series production. Molten metal is poured or pressed into a die, and overflows the cavity, in order to make sure that the complete part is casted (Dalquist and Gutowski, 2004). The die can be of different types, e.g. permanent molds of steel, salt cores, wax, ceramics or various minerals, referred to as sands (Campbell, 2011). A steel mold is a reusable die which can last up to a million castings (Dalquist and Gutowski, 2004). In other methods, the die is dissolved or spent after the casting process, which is a benefit in terms of the easy release of the casted product. Hence, the volume of production is very important when selecting a suitable method for casting. As regards the terminology used, ‘die casting’ mostly refers to the use of a permanent mold. The method is often divided further into gravity fed, low pressure or high pressure die casting. Confusingly, the first two types are sometimes referred to as permanent mold casting, and then instead, is only the last one called ‘die casting’, especially in the US (Campbell, 2011).

The major steps in the die casting process are die preparation, metal preparation, casting and finishing. Around 30% of the input aluminum can be expected to derive from scrapped material (Dalquist and Gutowski, 2004). The metal melting is commonly conducted using natural gas heating whereas other processes use electricity (Heinemann, 2016). Direct emissions mainly derive from the burning of the natural gas, but oil based lubricants used in the die preparation and casting, also produce VOC emissions from the casting process, which are not caused by the energy consumption (Dalquist and Gutowski, 2004). Metal scrap and dross is generated in each step and to a large extent recovered and remelted within the casting facility. However, some metal fumes of aluminum are lost as emissions to air in both preparation and casting, and some of the dross, filings and other metal losses are lost as waste (Heinemann, 2016).

Data collection

Data for aluminum die casting was collected in another LCI model project, describing a scalable inventory for a permanent magnet electrical machine (Nordelöf et al., 2017). The same data was used here. It was compiled from Roberts (2003), Dalquist and Gutowski (2004) and (Heinemann, 2016) for casting in a permanent steel mold. The energy figures reflect the average use of electricity and heat at 19 different die
casting foundries in Europe (Heinemann, 2016). Hence, it also includes building services such as ventilation, heating and general use of electricity, for example for lighting. The raw material for the steel mold has not been included, as a simplification, since it can be assumed to have a very small contribution per part in large scale production.

The process input for the die casting process is presented in Table 27 and emissions and waste in Table 28. All data have matching datasets in the Ecoinvent 3 database (Weidema et al., 2013). For the use of natural gas in this process, it is recommended to use the Ecoinvent 3 activity for “heat production, natural gas, at boiler atmospheric low-NOx non-modulating <100kW”, which represent a small natural gas furnace for industrial purposes. For the aluminum input, the recommended linked flow represents primary aluminum only, as a first-order approximation, to avoid an underestimation of the environmental load for the aluminum use.

### Table 27: Process input for die casting of 1 kg of aluminum.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum$^1$</td>
<td>1.06 kg</td>
<td>Heinemann (2016)</td>
<td>E3, aluminium, primary, ingot</td>
</tr>
<tr>
<td>Heat, from natural gas</td>
<td>10.8 MJ</td>
<td>Heinemann (2016)</td>
<td>E3, heat, central or small-scale, natural gas</td>
</tr>
<tr>
<td>Electricity</td>
<td>2.6 kWh</td>
<td>Heinemann (2016)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Lubricating oil</td>
<td>20 g</td>
<td>Approx. from Roberts (2003)</td>
<td>E3, lubricating oil</td>
</tr>
</tbody>
</table>

Note 1: In practice often 70% virgin aluminum and 30% scrap aluminum.

### Table 28: Emissions and waste from die casting of 1 kg of aluminum.

<table>
<thead>
<tr>
<th>Emissions to air$^1$</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked elementary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.4 g</td>
<td>Heinemann (2016)</td>
<td>E3, aluminium, unspecified</td>
</tr>
<tr>
<td>VOC</td>
<td>1 g</td>
<td>Dalquist and Gutowski (2004)</td>
<td>E3, NMVOC</td>
</tr>
<tr>
<td>Solid waste</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waste aluminum$^2$</td>
<td>60 g</td>
<td>Heinemann (2016)</td>
<td>E3, waste aluminium</td>
</tr>
</tbody>
</table>

Note 1: The emissions from the burning of natural gas has not been included and must be added separately (for example by using the recommended linked flow in Ecoinvent, given in Table 27).

5.4.3 Machining

Die cast aluminum casing parts must go through machining before they are apt for final assembly. The fitting of the lid and housing compartment must be precise. The compartment and heatsink may have been molded in sections that must be fitted and mounted with high precision, for example to incorporate a complex cooling channel structure. Excessive material has to be removed from the workpiece, and holes or other types of fixation points must also be prepared. Typically, this step involves multiple operations such as turning, cutting, drilling, milling and threading. In order to join all parts perfectly, several guiding edges and tightly matched surfaces must be trimmed, and the time necessary for this surface finishing depends on the total area with specific tolerance requirements. Another significant part of the processing time is coupled to milling and drilling operations aiming to prepare screw holes, fixation points, and nozzles and channels for the cooling system (Walter, 2016). The finishing of the housing compartment’s inner bottom surface is also important since especially the power module baseplate must have good contact and heat conduction to the heat sink. Aluminum scrap, mostly in the form of aluminum shavings, but also dust, is generated during the machining, and it must be removed in a cleaning step before the assembly.

**Data collection**

The raw data for preparing and trimming the die cast aluminum housing compartment and heatsink parts in a fully automatized multi-operating machine, was taken from an analogous process of trimming die cast aluminum electrical machine housings, collected at ELMO Malmköpings Mekaniska Werkstad AB (Karlsson, 2013, Walter, 2015, 2016) in Flen, Sweden. Information was also collected from Iro AB, an electrical machine
manufacturer in Ulricehamn, Sweden (Magnusson, 2016). The original raw data was collected as described in detail by Nordelöf et al. (2017) in a similar LCI model project.

In summary, it was observed that large die cast parts generally have less excess material per kilogram of die cast metal, compared to small parts. It was also found that surface trimming is a time consuming step compared to operations were larger amount of excess material is removed at the same time, such as cutting of sprues, drilling holes or milling with less precision. Surfaces typically have an average machining allowance of about 0.7 mm which is removed from the workpiece (Magnusson, 2016). Hence, the more surface area to trim and other high precision tasks, the more time consuming becomes the machining step.

However, due to the rather straightforward rectangular block structure of the inverter casing, it was found that surface areas with trimming requirements have a roughly linear growth with the total die cast mass, when comparing the casings of the two reference inverter units for liquid cooled heatsink option. It was also noticed that larger casings require more threaded screw holes and larger threaded openings cable glands. Hence, in a simplified and low estimate compared to the electrical machine housing bodies (Nordelöf et al., 2017), it was calculated that 5% of the die cast aluminum mass is removed in the machining step, for all housing compartment and heatsink options. One third of the mass is removed during surface trimming, with a speed of 16 grams per minute, based on a geometric assessment of the reference units. The remaining machining steps, and related mass removal, were assessed with a fixed operating time of 5 minutes.

On average, the multi-operating machines were found to use 3 kWh of electricity per hour of active operation. The machine use 13 grams of cutting fluid per minute of operation. It is mixed with water to generate 0.25 kg of diluted waste oil per minute.

Data for the cleaning of parts after machining was applied without modification from Nordelöf et al. (2017). In this case, the machined die cast parts are cleaned using compressed air blowers. An analysis made on the use of pneumatics at ELMO (Karlsson, 2013, Walter, 2015, 2016), showed that it draws about 0.5 kWh to clean one motor housing with compressed air. The same data was used here, per inverter casing. Notably, compressed air use is very energy demanding. The reason is that relatively short active operations carry a load of losses from compressor heat and air leakage, also occurring during standby.

The presented data is summarized in tables 29-30.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Die cast aluminum</td>
<td>1.05 kg</td>
<td>Calculated.</td>
<td>IF, see Section 5.4.2.</td>
</tr>
<tr>
<td>Electricity, trimming</td>
<td>0.06 kWh</td>
<td>Machine measurements combined with geometry estimates, see Nordelöf et al. (2017) for further raw data description.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Cutting fluid, trimming</td>
<td>14 g</td>
<td></td>
<td>E3, naphtha</td>
</tr>
<tr>
<td>Water, trimming</td>
<td>0.26 kg</td>
<td></td>
<td>E3, tap water</td>
</tr>
<tr>
<td>Process input</td>
<td>Amount per piece</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Electricity, other machining</td>
<td>0.25 kWh</td>
<td>Machine measurements combined with geometry estimates, see Nordelöf et al. (2017) for further raw data description.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity, cleaning</td>
<td>0.5 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Cutting fluid, other machining</td>
<td>65 g</td>
<td></td>
<td>E3, naphtha</td>
</tr>
<tr>
<td>Water, other machining</td>
<td>1.20 kg</td>
<td></td>
<td>E3, tap water</td>
</tr>
</tbody>
</table>

Table 29: Process input for the machining of the die cast aluminum casing, given per 1 kg of finalized casing or fixed, per readymade piece, depending on the task of the multi-operating machine.

<table>
<thead>
<tr>
<th>Waste</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum scrap</td>
<td>53 g</td>
<td>See Table 29.</td>
<td>Aluminum scrap, for recycling</td>
</tr>
<tr>
<td>Waste oil, diluted, trimming</td>
<td>14 g</td>
<td></td>
<td>E3, waste mineral oil</td>
</tr>
<tr>
<td>Waste</td>
<td>Amount per piece</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Waste oil, diluted, other</td>
<td>65 g</td>
<td>See Table 29.</td>
<td>E3, waste mineral oil</td>
</tr>
</tbody>
</table>

Table 30: Waste from the machining of the die cast aluminum casing, given per 1 kg of finalized casing or fixed, per readymade piece, depending on the task of the multi-operating machine.
5.4.4 Spray painting

Paint coatings can be applied either as a liquid or as a powder. The final result is essentially the same, and the applied coating consist of a solidified resin, with pigments added to provide color, if it is desired. The selection between a powdered resin and a liquid varnish where the resin comes in solution with a solvent, is mainly a selection of the application method (SAF, 2016). Powder coatings generally require larger batches. Also, some resins are more easily manufactured in liquid form, others as powders (SAF, 2016). In both cases, it is common to apply the coating by spraying. However, a main difference is that the liquid paint solvent is emitted to air when the paint is cured, typically classified as volatile organic compound.

Data collection

The data used for the painting of the die casted casing was based on a compilation described by Nordelöf et al. (2017), similar to the procedure described in Section 5.4.3. Hence, the original data collection was made for spray painting of varnish suitable for automotive electrical machine housings, and other similar applications in vehicles. The data was judged equally valid for the inverter unit casing.

Process inputs and emissions from painting were assembled from the supplier of the selected varnish (Von Roll, 2013, Larrenduche, 2015) and the solvent sub supplier (ExxonMobil, 2007, 2014). It was combined with the overall assessment of the compressed air system at the factory, since the spray painting equipment was found to be pneumatically propelled (Nordelöf et al., 2017). The spray painting inventory calculations were conducted for an air flow rate of 200 liters per minute and a paint flow rate of 200 ml per minute. The solid mass share of the varnish is 52% and the liquid density is 0.9 grams per liter (Von Roll, 2013). The remaining 48% of the mass consists of solvent which evaporates as VOCs during the curing (ExxonMobil, 2014). The compilation of the data is shown in Table 31 and Table 32.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per 100 g</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid varnish, solid share</td>
<td>100 g</td>
<td>Von Roll (2013)</td>
<td>E3, alkyd resin, without water</td>
</tr>
<tr>
<td>Liquid varnish, solvent share</td>
<td>92 g</td>
<td>Von Roll (2013)</td>
<td>E3, naphtha</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.56 kWh</td>
<td>See Nordelöf et al. (2017)</td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>

Table 31: Process input for spray painting, per 100 g dried varnish on the casing surface.

<table>
<thead>
<tr>
<th>Emissions to air</th>
<th>Amount per 100 g</th>
<th>Source</th>
<th>Linked elementary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOC</td>
<td>92 g</td>
<td>Von Roll (2013), ExxonMobil (2014)</td>
<td>E3, NMVOC</td>
</tr>
</tbody>
</table>

Table 32: Emissions to air from spray painting, per 100 g dried varnish on the casing surface.

5.4.5 Anodizing

Successful anodizing of aluminum requires that the surface is clean and free of oxides before the process starts. Accordingly, similar to the electroplating of copper and steel, described in section 5.2.3, it begins with chemical cleaning. If the part is heavily soiled, the first step may be solvent cleaning. Otherwise, as before plating, it is common that alkaline cleaning is followed by acid cleaning (Davis, 1993). However, electrocleaning is seldom used for aluminum parts (Davis, 1993).

Next, the part is immersed in an acid solution and an electric current is applied to build the protective aluminum oxide layer on the surface. In conventional anodizing, about two thirds of the anodizing layer penetrates into the aluminum part, and one third is a buildup over the original surface (Osborn, 2014). For hard anodizing, when the layer becomes thicker because it is conducted at higher temperature, voltage and current density, the buildup is closer to 50% (Davis, 1993, Osborn, 2014). The part acts as the anode in the electrochemical process, explaining the name of the method. Two different acids are dominating in conventional anodizing of aluminum, sulfuric acid and chromic acid. If some areas are to be kept free of the anodic coating, they must be masked. This is referred to as “selective anodizing” and masking can be done using plugs or lacquers, but tapes are likely most common. Tapes are typically made of foiled polyester, e.g. Mylar, layered with a pressure sensitive adhesive (Davis, 1993). The final step of anodizing is sealing where
the purpose is to close the pores of aluminum oxide layer. The part is immersed into a final bath of water at boiling temperature (Davis, 1993, Shang et al., 2016).

**Data collection**

Data for anodizing was primarily gathered from Davis (1993). The information found was judged to be valid for current processes despite age of the original source, by comparison with newer publications (Osborn, 2014, Shang et al., 2016), but with less comprehensive coverage of the process. The oxide layer thickness, 20 µm (presented in section 4.2.4), corresponds to conventional anodizing. It was found representative based on examples of other anodized automotive powertrain parts (Davis, 1993). There is a general dataset for anodization of aluminum available in the Ecoinvent database (Weidema et al., 2013). However, since new primary data was found for automotive parts, the new dataset was established.

First, solvent cleaning was assumed unnecessary owing to the pneumatic cleaning following the machining step. The volume of chemicals and rinsing water consumed per square meter of surface area found for electroplating was judged equally valid here. Hence this data, as well as the complete alkaline cleaning step (see section 5.2.3), derives from Moing et al. (2009). The acid bath for cleaning consists of nitric acid and sodium sulfate heated to 80°C (Davis, 1993). The anodizing bath is a mix of 20% sulfuric acid and 80% water, by mass. The electricity used was calculated from tabulated operating data to create a 20 µm coating layer over a 30 minute operating cycle. Electricity for heating the acid bath to operating temperature and the final deionized water sealing bath to boiling, was also calculated roughly and included.

The material requirement and composition of a 100 µm thin tape suitable for masking was also checked and included for completeness (3M, 2004). It weighs 130 g/m² of masked area (Carbex, 2015, KCC, 2007), but calculated per m² of anodized surface area, it was rounded to 5 grams of tape for this specific casing design. It is made of 75% polyester foil and 25% silicone adhesive. After the final rinsing, it is assumed that the tape is removed by hand and disposed as plastic waste.

A summary of the process inputs is present in Table 33, including recommended linked flows for coupling the each data to Ecoinvent version 3 (Weidema et al., 2013). As in the case with electroplating, the rinsing water was assumed go through internal wastewater treatment at the anodizing facility plant. Also, a similar simplification was made for the data and “wastewater, average” is used for the linked flow to Ecoinvent (Weidema et al., 2013), to model the wastewater processing, see Table 37.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>1 kWh</td>
<td>Calculated from Davis (1993)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Caustic soda</td>
<td>10 g</td>
<td>Moing et al. (2009)</td>
<td>E3, sodium hydroxide, without water</td>
</tr>
<tr>
<td>Nitric acid</td>
<td>4 g</td>
<td>Calculated from Davis (1993)</td>
<td>E3, nitric acid, w/w water, in 50% sol. state</td>
</tr>
<tr>
<td>Sodium sulfate</td>
<td>3 g</td>
<td>Calculated from Davis (1993)</td>
<td>E3, sodium sulfate, anhydrite</td>
</tr>
<tr>
<td>PET foil</td>
<td>3.8 g</td>
<td>3M (2004), KCC (2007), Carbex (2015)</td>
<td>IF, see section 5.3.2.</td>
</tr>
<tr>
<td>Silicone adhesive</td>
<td>1.2 g</td>
<td></td>
<td>E3, silicone product</td>
</tr>
<tr>
<td>Water</td>
<td>24 kg</td>
<td>Davis (1993), Moing et al. (2009)</td>
<td>E3, water, deionized, from tap water, at user</td>
</tr>
</tbody>
</table>

**Table 33: Process input for anodizing 1 m² of aluminum surface area, including masking tape in amounts adopted for the specific casing design.**

<table>
<thead>
<tr>
<th>Liquid waste</th>
<th>Amount per m³</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater</td>
<td>24 dm³</td>
<td>Matching rinsing water</td>
<td>E3, wastewater, average</td>
</tr>
<tr>
<td>Solid waste</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
</tbody>
</table>

**Table 34: Waste from anodizing 1 m² of aluminum surface area, including masking tape in amounts adopted for the specific casing design.**
5.5 Power module fabrication

5.5.1 Overview

Figure 25 shows an overview of the alumina substrate factory and the DCB plant, as included in the LCI model. Next, the DCB continues to nickel plating (see Section 5.2.3) before it enters the power module assembly factory, shown in Figure 26.

Figure 25: Overview of the DCB manufacturing steps.
Figure 26: The power module assembly.
As presented in Figure 25, the fabrication of the power module starts with the making of the ceramic alumina substrate from a powder. Next, the sintered ceramic substrate is joined with two copper foils in a direct bonding process into a DCB. The upper foil of the DCB is etched to receive the required circuitry. All these processes, from the start to the point where the DCB is ready for electroplating, were grouped into three unit process datasets, which are described in sections 5.5.2-5.5.4.

Subsequently, the power module assembly procedure (Figure 26) include three main cleanings steps which are scattered in the process flow but described together in Section 5.5.8. The soldering dataset (Section 5.5.5) describes how the semiconductor chips, the baseplate and contacts of the main terminals all are attached to the DCB. A description of the bonding of wires and terminal contacts is presented in Section 5.5.7. The plastic frame with plated and integrated terminals, silicone gel and the lid are joined with the DCB and baseplate into one part by screwing, potting and gluing, all summed up in Section 5.5.6. As it can be noticed, this division of subsections is not presented in the correct order of events. Instead, it was found more intelligible to group similar procedures or with the same purpose, rather than to follow the chronological order.

5.5.2 Ceramic substrate fabrication

The ceramic substrate is fabricated from alumina powder in a tape casting process (Blackwell, 2000). The powder is mixed and milled in a slurry made up of solvent, a binder, a plasticizer and a dispersant (Bengisu, 2001). Mixing and milling can take place at the same time in a ball mill. The slurry is fed onto a moving carrier and flattened out with a blade before it is dried and stamped from the thin sheet of “green tape” into the desired shape. The solvent evaporates during the drying phase. In the next step, the substrate is sintered at 1600-1700°C. Sintering times can differ from 20-60 minutes, for rapid-rate sintering of small batches (Bengisu, 2001), up to 24 hours for industrial scale manufacturing with large continuous throughput of substrates (Hedlund, 2017). Modified atmospheres are sometimes used, for example hydrogen or oxygen (Bengisu, 2001), but air is used in established industry procedures (Hedlund, 2017). The selection of the different sintering parameters depend on, for example, the desired grain size, porosity and surface texture. Still, the effect is that green body densifies to its final substrate shape. The remaining organic components added to the slurry burn-out as emissions to air during the firing step (Blackwell, 2000).

Tape casting is a common and low cost method to produce ceramic substrates for electronic applications, typically made of alumina or aluminum nitride (Blackwell, 2000, Volke and Hornkamp, 2012). This process, as well as the conditions and temperatures in sintering step, are very similar for other thin ceramic products, for example electrolytes and electrodes for solid oxide fuel cells made of yttria-stabilized zirconia (YSZ) (Yuping et al., 2000, Bengisu, 2001, Pehnt, 2003).

Data collection

Alumina powder is generated through the Bayer process (Classen et al., 2009). This product, represented in the Ecoinvent 3 database (Weidema et al., 2013), was taken as the starting point for the substrate fabrication. The alumina mass, calculated from the scaled power module material content, was transformed into area by combining a substrate density of 3.8 kg/cm³ with the assumption that the substrate is 500 µm thick, which is a typical substrate thickness (KCC, 2012). The area calculated for the substrate in the large reference power module was found to match very well with the geometric estimations made by visual inspection, confirming the thickness assumption.

Yuping et al. (2000) describes a slurry recipe where highly pure water is the solvent. Alumina constitutes 55% of the slurry, by mass. Remaining main constituents were rounded to: 35% water, 4% acrylic binder (polyvinyl acetate, PVA), 5% plasticizer (glycerin) and 1% acrylic dispersion (ammonium polyacrylate). All substances were found to have suitable datasets for flows linking to Ecoinvent 3 (Weidema et al., 2013). Losses of slurry occur in milling and tape casting machinery, and about 1% of the total slurry blend was assessed a going to waste (European Comission, 2007).

Data for the electricity consumption was gathered from Hart et al. (2000). They have presented and compared energy use data for the manufacturing of solid oxide YSZ ceramics for fuel cells, both including data for the different process step more detailed to make a 50 µm thick YSZ electrolyte and, aggregated, to make a 500 µm nickel-YSZ anode. The dataset includes slurry mixing and milling, tape casting, stamping, drying and a 24 hour sintering heat cycle with an average output of more than 10 m² total substrate area per hour (Hart et al., 2000). It also includes building services such as ventilation. Here, it was taken as a proxy for the complete tape casting and sintering process of the alumina substrate with some small modifications. Hart et al. (2000) find that the 500 µm thick anode require 22.6 kWh/m² in total to fabricate. The data for ball milling and tape casting was adjusted for the fact that alumina has a different density than YSZ. The resulting
total energy use was set to 21 kWh/m², with sintering being the main consumer of electricity. The furnace was assumed to operate with air.

Emissions to air generated by the burn-out of the organic compounds were assessed based on the information about main decomposition products provided by their technical specifications and tabulated substance data (ScienceLab, 2013b, d, Vanderbilt, 2014, Haynes, 2016). Given this simplification, 20% of the dispersant mass evaporates as ammonia and the remainder as volatile organic compounds. For the binder and plasticizer, it was presumed that half of the carbon content decompose into carbon monoxide and the other half into carbon dioxide.

Tables 35-36 present the compiled dataset, including linked flows to Ecoinvent 3 (Weidema et al., 2013).

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium oxide</td>
<td>1.92 kg</td>
<td>Yuping et al. (2000)</td>
<td>E3, aluminium oxide</td>
</tr>
<tr>
<td>Electricity</td>
<td>21 kWh</td>
<td>Adj. from Hart et al. (2000)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Ammonium polyacrylate</td>
<td>35 g</td>
<td>Yuping et al. (2000)</td>
<td>E3, acrylic dispersion, w/w water, in 65% sol. state</td>
</tr>
<tr>
<td>Glycerin</td>
<td>0.17 kg</td>
<td>Yuping et al. (2000)</td>
<td>E3, glycerine</td>
</tr>
<tr>
<td>Polyvinyl alcohol</td>
<td>0.14 kg</td>
<td>Yuping et al. (2000)</td>
<td>E3, acrylic binder, w/w water, in 34% sol. state</td>
</tr>
<tr>
<td>Pure water</td>
<td>1.22 kg</td>
<td>Yuping et al. (2000)</td>
<td>E3, water, ultrapure</td>
</tr>
</tbody>
</table>

Table 35: Process input per 1 m², for the fabrication of a 500 µm thick alumina substrate.

<table>
<thead>
<tr>
<th>Emissions to air</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked elementary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>7 g</td>
<td>Vanderbilt (2014), Haynes (2016)</td>
<td>E3, ammonia</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>77 g</td>
<td>ScienceLab (2013b, d), Haynes (2016)</td>
<td>E3, carbon dioxide</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>49 g</td>
<td>ScienceLab (2013b, d), Haynes (2016)</td>
<td>E3, carbon monoxide</td>
</tr>
<tr>
<td>VOC</td>
<td>28 g</td>
<td>Vanderbilt (2014), Haynes (2016)</td>
<td>E3, NMVOC</td>
</tr>
<tr>
<td>Solid waste</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Slurry waste</td>
<td>0.38 kg</td>
<td>European Comission (2007)</td>
<td>E3, hazardous waste, for incineration</td>
</tr>
</tbody>
</table>

Table 36: Emissions and waste per 1 m², from the fabrication of a 500 µm thick alumina substrate.

5.5.3 Direct copper bonding

In the direct copper bonding process the copper foils are placed in contact with the ceramic substrate and they are sent together into a furnace with an inert gas, nitrogen or argon, and about 0.4 % in weight of oxygen (Burgess and Neugebauer, 1973, Torrey Hills, 2017). The temperature cycle is regulated very precisely to oxidize the copper in thin layer on the surface of the foils and just above 1065°C this layer melts and forms a “eutectic”. It creates a strong bond directly between the substrate and the foils. It is important that the temperature still remains below the melting point of copper at 1083°C (Burgess and Neugebauer, 1973). During the cool down, any remaining oxide may be reduced by supplying hydrogen (Burgess and Neugebauer, 1973), but this step is often left out (Lenz, 2014). More important for the quality of the bonding is proper pre-oxidation which can be achieved by heating the parts to 300°C and then holding the oven temperature for one hour in air (Ning et al., 2003).

Both copper foils and the ceramic substrate requires cleaning prior to the bonding process (Ning et al., 2003, Ghasemi et al., 2008). For the alumina substrate this may be done by ultrasonic cleaning, i.e. using ultrasonic waves transmitted in a liquid bath (Ning et al., 2003, Ghasemi et al., 2008). Copper foils are degreased using acids and sometimes also cleaned ultrasonically (Ning et al., 2003, Ghasemi et al., 2008).

Data collection

First, data was gathered for the cleaning. According to Ning et al. (2003), copper foils can be cleaned by dipping in hydrochloric acid for three minutes and then ultrasonically in a bath of deionized water and cleaning alcohol for 10 minutes. Substrates are instead treated ultrasonically in two baths: one with water and a second with acetone and cleaning alcohol (Ning et al., 2003). A description of small scale ultrasonic batch cleaning
machine for dental devices was available from Unger and Landis (2014), used for the electricity consumption and the volume of the tank. The small machine size was regarded as sufficiently representative, although larger batch machines may be used in high volume production. At full load, i.e. one complete batch, the tank contains 32 substrates or foils on a rack when the DCB has the size of the 80 kW reference unit, based a supplier’s recommendations for the load level of ultrasonic cleaning tanks (TM, 2010). For simplicity, it was assumed that identical tanks and racks are used also for the acid dip cleaning step of the foils. The concentration of the hydrochloric acid was set to 30%, as available in Ecoinvent 3. In the two baths containing cleaning alcohol, isopropanol was assumed to be mixed with 50% water or acetone, respectively (Ning et al., 2003). No data was found for the replacement scheme for the bath solutions. Instead, it was assumed that all baths are replaced after the cleaning of 100 batches, based on information for the replacement of ultrasonic washing liquids at Aros (see section 5.1.3). All liquids were expected to be disposed for treatment as spent solvent mixture.

All examples of industrial controlled atmosphere furnaces suitable for processing DCBs were found to be belt furnaces (BTU, 2013, Lenz, 2014, Torrey Hills, 2017). Accordingly, belt furnace data was selected for the model. Ning et al. (2003) describes a 5.5 hour long operating scheme including one hour for pre-oxidation at 300°C. This temperature cycle was confirmed as representative for industrial practices by Lenz (2014). The data for energy consumption of the belt furnace was established by recalculating data for pre-heating and continuous operation of a six temperature zone belt furnace presented by Franz and Weilguni (2011). They measured the energy consumption of a furnace (BTU, 2013) during the lamination of six-layered co-fired ceramic substrates. A simple model of the furnace was established where the electric energy consumption for heating was recalculated to kWh per Kelvin and length of the active heat zones, both for pre-heating and for continuous operation in a 24 hour cycle. It was then adjusted to match the heating zones required for the for direct copper bonding profile presented by Ning et al. (2003). The throughput of the furnace and the energy consumption were correlated using the result for a specific sample in the original study. A 1.8 mm thick sample (CeramTec, 2010) was found to be most appropriate, with a furnace energy consumption of 0.98 kWh/sample and a regular feed of new samples over a 24 hour test period (Franz and Weilguni, 2011).

Franz and Weilguni (2011) also report the energy consumption of a flow gas compressor, but point out that the figure is high (Franz and Weilguni, 2011). Data for the nitrogen flow gas was based on Ghasemi et al. (2008) and more representative data for the compressor energy consumption was found by matching the gas flow rate with pump data from (Gast, 2012). Overall, in line with typical industrial furnaces, the efficiency was assumed to be low and the majority of all heat to be unproductive (Kruzhanov and Arnhold, 2012). Consequently, despite differences in the thermal properties between the DCB and the co-fired ceramics, the rescaled furnace data was judged to be a reasonable approximation. The final calculations were setup assuming 16 hours of production over a five day working week. The furnace was assumed to be shut off once a week.

Furnace ventilation was included using Aros plant data (recalculated to match the bonding cycle throughput instead of reflow throughput) (Aros, 2013, 2014b, c, f, Welin, 2014a, b). The furnace ventilation was assumed to run continuously without being turned off.

After the bonding process, each DCB consists of a 500 µm thick alumina substrate sandwiched by two equally thick copper foils (Visser and Snook, 1995, Sheng and Colino, 2005). From visual inspection of examples (and in line with the scaling of the design), it was assumed that the foils cover 95% of the alumina surface on both sides. The summarized data for the bonding process is presented in Table 37 and Table 38.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, cleaning</td>
<td>1 kWh</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity, furnace</td>
<td>59 kWh</td>
<td>Est. from Franz and Weilguni (2011)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity, ventilation</td>
<td>15 kWh</td>
<td>Adapted from Aros data, see 5.1.3.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Acetone</td>
<td>90 g</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>E3, acetone, liquid</td>
</tr>
<tr>
<td>Deionized water</td>
<td>0.8 kg</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
<tr>
<td>Hydrochloric acid</td>
<td>150 g</td>
<td>Tank volume from TM (2010)</td>
<td>E3, hydrochloric acid, w/w, in 30% sol. state</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>260 g</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>E3, isopropanol</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>175 kg</td>
<td>Ghasemi et al. (2008)</td>
<td>E3, nitrogen, liquid</td>
</tr>
</tbody>
</table>

Table 37: Process input per 1 m² of DCB before etching, for cleaning and direct bonding of foils and substrate.

---

37 A glass ceramic sample made of alumina and anorthite, called CeramTec CG (CeramTec, 2010).
5.5.4 Etching of the conducting pattern

In the photolithographic etching step the upper copper foil of the DCB is turned into a conducting pattern similar to that of a PCB (KCC, 2012, Sheng and Colino, 2005). A difference is that the DCB is etched in only one patterning process (without iteration), removing copper from one relatively thick foil layer, whereas a PCB is etched in all of its layers. Initially the DCB is cleaned and then coated with an UV sensitive and etching-resistant organic “photoresist” (OECD, 2004, Coombs, 2008). Acetone can be used for cleaning and removing organic impurities, often in combination with isopropanol (Walker and Tarn, 1991). The resist can be applied as a liquid coating or as a dry-film, but in both cases the part is heated in a pre-baking or a drying process. The resist is adhered in a desired image by exposure to UV light applied using a photo mask. Photoresists are typically polymer-based and include photoactive molecules dissolved in a solvent. They can be positive, i.e. become more soluble by UV light exposure, or negative, meaning that they stabilize. There are many options possible, such as isoprene and different variants of poly-methacrylate and ethyl acrylate (OECD, 2004). The energy intensity required in the form of UV light is relatively low, typically in the range of 25-90 mJ/cm² (70-250 mW/m²) for PCB imaging and 200-500 mJ/cm² (0.55-1.4 Wh/m²) for semiconductor imaging. Subsequently, non-adhered resist is washed away with a corresponding “developer”, and the DCB is dried again before the upper foil is etched in the exposed pattern to remove copper. Sodium or potassium carbonate are often used as developers for PCBs (Coombs, 2008, Kuehr and Williams, 2003, Siddhaye and Sheng, 1997). Other examples of are, sodium hydroxide, potassium hydroxide, ethylene glycol, ethanolamine and isopropyl alcohol (Coombs, 2008, OECD, 2004) Similarly, there are many options for stripping chemicals to remove the remaining photoresist, but potassium hydroxide is the most common example for PCBs (Kuehr and Williams, 2003). Notably, there are also many rinsing steps in photoimaging and it is generally very water intensive (Williams et al., 2002, Kuehr and Williams, 2003).

Regarding etching solutions, the use of cupric chloride is among the most common (Cakir, 2006, Coombs, 2008). It can be operated continuously by regeneration of the etchant in a loop (Cakir, 2006, Coombs, 2008, Chemcut, 2012). Regenerative etching systems can be based on chlorine gas, hydrogen peroxide, sodium chloride or electrolysis (Cakir, 2006, Coombs, 2008). Chlorine gas systems are often selected because they are cost effective and easy to control, but the method is regulated and sometimes avoided for safety reasons (Cakir, 2006). The process requires continuous addition of water besides chlorine gas. Hydrochloric acid is used to increase the etch rate by dissolving copper oxide and keeping the cupric chloride in a proper solution state (Chemcut, 2012). The copper that is etched off the DCB is recovered as excess cupric chloride and can be sold as a by-product.

**Data collection**

It was assumed that the foil cover 95% of the total substrate area (both sides) before etching and 90% after etching in line with data from KCC (2012). Specific data for photolithographic patterning of DCBs was not found for cleaning, resist coating, oven baking, developing and stripping. Instead, the data for the drying processes was approximated from the hardening oven for the conformal coating of PCBs Aros Electronics, described in section 5.1.3, but adapted to a slightly higher drying temperature, as prescribed for PCB photo imaging by Think & Tinker (2017). However, the throughput of the drying oven was also adjusted compared to the original Aros data, to match Aros’ yearly throughput of board area in the reflow ovens. This was done to comply with the adopted principle of modeling the throughput for a full production load when data is reworked (see Section 2.2). The total time for oven drying is about 20 minutes per DCB (Think & Tinker, 2017), which is equal to the total hardening process of the PCB conformal coating (Edgren, 2015). The energy required for UV exposure was neglected.

The amount of chemicals (i.e. excluding the regenerative etching step) were estimated from data for patterning of semiconductor wafers in several layers, particularly for integrated circuits, gathered from Williams et al. (2002), by combining it with information from textbooks (Greig, 2007, Mack, 2006) and a technical report (OECD, 2004). It was assumed that inflows and outflows are correlated with the surface area, both the data collection and in the presentation of data here. The figures from Williams et al. (2002) were

<table>
<thead>
<tr>
<th>Liquid waste</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste solvents, conc. share of dilution</td>
<td>0.5 kg</td>
<td>Calculated</td>
<td>£3, spent solvent mixture</td>
</tr>
</tbody>
</table>

Table 38: Waste per 1 m² of DCB before etching, for cleaning and direct bonding of foils and substrate.
recalculated to processing of one surface layer only and the chemicals were classified into cleaning agents, developers, resists and strippers, based on information from OECD (2004). Differing from circular wafers, where about 25% of the treated surface area around the perimeter is scrapped (Williams et al., 2002), it was assumed that the photolithographic chemicals are applied only on the specified substrate area. In addition, the recalculation also took into account that the making of an integrated circuit typically requires around 25 (within 20-30) iterative imaging cycles (Greig, 2007, Mack, 2006), whereas the substrate production only requires one photomask. Due to the many different options for the photoresist, it was not specified as an explicit compound. Instead, for the upstream linked flows to Ecoinvent 3 (Weidema et al., 2013), it is recommended to be modeled as an average organic chemical. The developer and the stripper were remodeled to potassium carbonate and potassium hydroxide, respectively, based on the general background (presented above).

The regenerative etching step was modeled with data collected from Chemcut (2010, 2012), specifying the process settings as well as the rating for power and the throughput of the cupric chloride system machine, built for regeneration based on chlorine gas. This data is presented per kilogram of etched copper.

For emissions and waste, the solvent fraction of the photoresist can be expected to evaporate as an emission to air in the drying process (OECD, 2004). As a simple but reasonable assumption, 50% of the mass is released as volatile organic compounds. Excess cupric chloride from the etching step is collected and shipped off for further treatment. All liquid waste chemicals follow with the rinsing water to be collected in tanks for further waste handling as spent solvent mixture.

Finally, water use data was not available specifically for photoimaging such that it could be broken down and modeled for the separate steps of the DCB patterning. Instead, data for the amount of water consumed in each rinsing step during electroplating was found representative and applied as described by Moing et al. (2009), see section 5.2.3. Rinsing with water was modeled to take place after solvent cleaning, developing and stripping (see Figure 25). The resulting process inputs and outputs for the etching of the conducting pattern are presented in tables 39-40.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>13 kWh</td>
<td>Est. from Aros data, see 5.1.3.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Acetone</td>
<td>0.6 kg</td>
<td></td>
<td>E3, acetone, liquid</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>0.6 kg</td>
<td></td>
<td>E3, isopropanol</td>
</tr>
<tr>
<td>Photore sist</td>
<td>0.45 kg</td>
<td></td>
<td>E3, chemical, organic</td>
</tr>
<tr>
<td>Potassium hydroxide</td>
<td>1.3 kg</td>
<td></td>
<td>E3, potassium hydroxide</td>
</tr>
<tr>
<td>Water</td>
<td>24 kg</td>
<td>Est. from Moing et al. (2009)</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>0.2 kWh</td>
<td>Chemcut (2010)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Chlorine gas</td>
<td>1.1 kg</td>
<td>Chemcut (2012)</td>
<td>E3, chlorine, gaseous</td>
</tr>
<tr>
<td>Hydrochloric acid</td>
<td>0.9 kg</td>
<td>Chemcut (2010)</td>
<td>E3, hydrochloric acid, w/w, in 30% sol. state</td>
</tr>
<tr>
<td>Water</td>
<td>6.6 kg</td>
<td>Chemcut (2012)</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
</tbody>
</table>

Table 39: Process inputs per 1 m² of DCB, or per 1 kg of copper removed, for the patterning of the DCB upper copper foil by photo imaging and regenerative etching.

<table>
<thead>
<tr>
<th>Emissions to air</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked elementary flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOC</td>
<td>0.23 kg</td>
<td>Calculated</td>
<td>E3, NMVOC</td>
</tr>
<tr>
<td>Liquid waste</td>
<td>Amount per m²</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Waste solvents, conc. share of dilution</td>
<td>4.3 kg</td>
<td>Calculated</td>
<td>E3, spent solvent mixture</td>
</tr>
<tr>
<td>Solid waste</td>
<td>Amount per kg</td>
<td>Source</td>
<td>Linked flow</td>
</tr>
<tr>
<td>Cupric chloride</td>
<td>2.1 kg</td>
<td>Calculated, Haynes (2016)</td>
<td>Cupric chloride for recycling</td>
</tr>
</tbody>
</table>

Table 40: Emissions and waste per 1 m² of DCB, or per 1 kg of copper removed, for the patterning of the DCB upper copper foil by photo imaging and regenerative etching.
5.5.5 Soldering the power module

The fabrication of the power module requires several different bonding processes. Soldering is among the key methods (Sheng and Colino, 2005). It is used in two particularly important joints: attaching the power chips to the DCB (called chip soldering or die attach) and the DCB to the baseplate (referred to as system soldering) (Volke and Hornkamp, 2012).

Traditionally, power module soldering has been conducted in a two-step approach with two different solders, i.e. with dissimilar melting points (Sheng and Colino, 2005). Chip soldering is the first step, and it requires a solder with a 25-40°C higher melting point than that of the second solder, used for system soldering and attaching terminals (Olszewski, 2006, Sheng and Colino, 2005). The point is to avoid that the chip solder melts during the system soldering, with the risk of chips slipping out of position and subsequent failure. The application of the solder can be made with stencil printing of paste or with “preforms”, where ready-made solder shapes are applied from a carrier tape. Chips are positioned on the solder with a pick and place machine and the unit enters the reflow oven. After completing the first round of reflow, the second solder is applied on the baseplate and the DCB, again using preforms, stencil printing or a dispensing machine. Subsequently, the baseplate, the DCB with mounted chips and often also the contacts to the power terminals and are placed together in a fixture, and the module is reflowed again, at a lower temperature (Sheng and Colino, 2005).

However, there are challenges with the two-solder approach. Especially, the power module must now be lead-free to become RoHS38 compliant, but the standard lead-free solder variants containing blends of tin, silver and copper all have melting points within a span of 218-240°C (Sheng and Colino, 2005). At the same time, it is desirable to allow an increase in the chip operating temperature, to achieve a higher power density of the module, even up to 200°C at the junction to the DCB (Guth et al., 2010). As a response, newer production methods have evolved over the last decade where joints with remelting temperatures above 400°C can be achieved using standard tin-silver solders and ordinary reflow oven peak temperatures of 240-260°C (Guth et al., 2010, Volke and Hornkamp, 2012, Khaja et al., 2013). The key is to reduce the thickness of the solder joint to somewhere between 10-15 µm and to apply pressure or vacuum during the reflow process (Guth et al., 2010, Khaja et al., 2013). Thin alloy phases are formed between the solder and the two metal surfaces to be bonded. The method is referred to as “diffusion soldering” (Guth et al., 2010, Volke and Hornkamp, 2012, Khaja et al., 2013). It is primarily used for the chip attachment (there is a thin metallization layer underneath the chip which is involved in the diffusion process), but it is also possible for the system soldering.

Consequently, a two-step method is still often used for soldering the power module, but diffusion soldering removes the requirement of different solder types. The main disadvantage is that the method requires more costly equipment compared to conventional convection reflow ovens (Sheng and Colino, 2005), described in Section 5.1.3. The stencil printing must be more precisely tuned and the use of vacuum must be combined with “vapor-phase soldering” (VPS) to achieve proper results, i.e. a vaporized liquid (consisting of perfluoropolyethers) is used to transfer heat to the soldering object (Leicht and Thumm, 2008, Khaja et al., 2013). However, VPS eliminates the need for a flow gas to create an inert environment inside the furnace and it is generally more energy efficient than the convection approach (Leicht and Thumm, 2008).

For more details about solder paste, stencil printing and cleaning, please read Section 5.1.3.

Data collection

The data for the power module soldering was estimated from the PCBs soldering data compiled at Aros Electronics AB (Aros, 2013, 2014a, c, d, e, f, g, Edgren, 2014, 2015, 2017), earlier described in Section 5.1.3, taking the difference in average power draw of vacuum VPS soldering and the specific diffusion soldering cycle time, compared to convection reflow soldering, into account. These modifications are described in the following.

First, it was assumed that the soldering of the module would be carried out in a two-step process using diffusion soldering in a vacuum VPS reflow oven for the chip attachment and a conventional convection reflow oven using nitrogen as the flow gas, for the system soldering. Both steps use the same type of solder as previously described for the design of the power module, i.e. Sn95.5Ag3.8Cu0.7 (but with the recommended linked flow to EcoInvent 3 stated as Sn95.5Ag3.9Cu0.6), in the form of paste with the same properties as reported for the PCB assembly at Aros, see sections 4.1.2 and 5.1.3. A description of diffusion soldering with similar SnAgCu solders for chip attachment of power modules has been provided by Khaja et al. (2013), including printing of solder paste on a 20 µm stencil and VPS reflow combined with vacuum, to form a 15 µm solder joint.

38 See footnote no. 6 on page 18, Section 4.1.2.
Consequently, the compiled dataset takes into account that the DCB and baseplate goes through stencil printing separately. All terminals and contacts are supposed to be pre-anchored in the frame (i.e. mounted and bonded in a later step), so they are not included in the soldering process. In addition, the chip mounted DCB is modeled to be is placed in a fixture onto the stenciled baseplate directly after the diffusion soldering step, i.e. without any intermediate cleaning, based on the use of no-clean flux and since the two step involve opposite sides of the DCB. Losses of solder paste was modeled as described for the driver and logic boards (Edgren, 2015) (Section 5.1.3). The energy consumption and the use of cleaning chemicals for the stencil printing are calculated from the DCB and the baseplate upper surface areas, consistent with the definition of board area for the PCBs. For this purpose, an area scale factor was established for the baseplate from measurements on the two reference units (Infineon, 2012a, 2014b). The starting value (for the 20 kW reference unit) came to 91 cm² and the scale factor to 1.63 cm²/kW of nominal inverter power. The energy for automated placing of chips on the DCB was neglected (based on the pick and place machine for the PCB SMDs, see Section 5.1.3).

Next, information was gathered for the refloving procedures. It was noted that the convection reflow ovens at Aros Electronics AB have higher continuous power draw (about 10 kW) (Edgren, 2015) compared to stated values for continuous reflowing in VPS ovens (5-6 kW) of the same size (Leicht and Thumm, 2008, IBL, 2017), but with some uncertainty regarding the energy use of the vacuum compressor. The required vacuum level is 15 mbar and this can be provided by pumps with a power draw around 1 kW (Edwards, 2014). Additionally, Zöllig and Schweizer (2013) exemplifies that vacuum compressors only stands for 2-5% of the energy consumption in large vacuum furnaces. Thus, it was found that the energy consumption can be expected to reduce by 30%-40% for the vacuum VPS furnace compared to a forced convection reflow oven.

However, this reasoning holds as long as both furnace types are of equal length and that they are running the same temperature profiles, or at least with the same peak temperature, since it is the most important factor for the energy consumption (Geibig and Socolof, 2005, Deubzer, 2007). The number of boards passing through the oven is less important for the total energy use of the furnace. In fact, Deubzer (2007) states that the total energy consumption of reflow ovens is nearly independent from the throughput for a specific reflow profile. Oppositely, the soldering time (related to the speed through the furnace) and the throughput becomes very important factors for the energy consumption per unit, and not only the furnace energy consumption.

For this reason, data for a typical reflow profile for SnAgCu solder in forced convection oven was collected from Coombs (2008) and compared with a profile presented by Khaja et al. (2013) for the diffusion soldering process. Both have the same peak temperature of 260°C, but the total time for the forced convection profile is around 7 minutes while the diffusion soldering takes 12 minutes (Khaja et al., 2013). Accordingly, the speed through the oven is slower and the throughput turn out to be, by coincidence, about 40% lower for the vacuum VPS diffusion soldering process. As a result, the increased energy efficiency of the vacuum VPS system was found to be balanced by a lower throughput and the electricity consumption values from Aros was used without modification for the chip attachment with diffusion soldering. Notably, VPS does not require nitrogen flow gas. As well, it was assumed that there is no net consumption of heat transfer liquid since is regenerated from vapor within the reflow oven, based on information from (Géczy et al., 2013).

Next, it was found reasonable that the reflow profile for the system soldering is similar to that of the PCBs measured at Aros, despite the much larger amount of solder being used. Consequently, the Aros values were used again without modification. All compiled data for the power module soldering is presented in tables 41-46.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>2.1 kWh</td>
<td>See Section 5.1.3.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Cleaning liquid, alkoxyp propane</td>
<td>65 g</td>
<td>See Section 5.1.3.</td>
<td>E3, dipropylene glycol monomethyl ether</td>
</tr>
<tr>
<td>Cleaning liquid, amino alcohol</td>
<td>10 g</td>
<td>See Section 5.1.3.</td>
<td>E3, monoethanolamine</td>
</tr>
<tr>
<td>Cleaning liquid, deionized water</td>
<td>320 g</td>
<td>See Section 5.1.3.</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
</tbody>
</table>

Table 41: Process inputs for the stencil printing and cleaning of stencils per 1 m² of DCB or baseplate (area on one side – not total surface area). The DCB and baseplate goes through stencil printing separately before the chip attachment and system soldering.

39 The baseplate mass and the total area subject to plating are also established within the LCI model, independently from this area scale factor. However, the plate varies both in thickness and as regards the number and dimensions of screw holes over the model range. Thus, additional information is required for the soldering calculations.

40 As an alternative, the belt speed and the throughput of the VPS oven could be the same as for the convection reflow oven, but then the oven must be longer in order to achieve the desired soldering profile.
Table 42: Liquid waste from the stencil printing and cleaning of stencils per 1 m² of DCB or baseplate (area on one side – not total surface area). The DCB and baseplate goes through stencil printing separately before the chip attachment and system soldering.

<table>
<thead>
<tr>
<th>Liquid waste</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disposed cleaning liquid, conc. share</td>
<td>75 g</td>
<td>See Section 5.1.3.</td>
<td>E3, spent solvent mixture</td>
</tr>
</tbody>
</table>

Table 43: Process input of lead-free solder paste per kg of lead-free solder in the power module, covering for both soldering steps.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder paste</td>
<td>1.25 kg</td>
<td>Recalculated, see Section 5.1.3.</td>
<td>E3, solder, paste, Sn95.5Ag3.9Cu0.6</td>
</tr>
</tbody>
</table>

Table 44: Solid waste and emissions to air per kg of lead-free solder in the power module, covering for both soldering steps.

<table>
<thead>
<tr>
<th>Solid waste</th>
<th>Amount per kg</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter waste</td>
<td>68 g</td>
<td>Recalculated, see Section 5.1.3.</td>
<td>E3, hazardous waste, for incineration</td>
</tr>
<tr>
<td>Solder paste waste</td>
<td>56 g</td>
<td>Recalculated, see Section 5.1.3.</td>
<td>Solder waste, optional recycling</td>
</tr>
<tr>
<td>Emissions to air</td>
<td>Amount per kg</td>
<td>Source</td>
<td>Linked elementary flow</td>
</tr>
<tr>
<td>Ethanol</td>
<td>37 g</td>
<td>Recalculated, see Section 5.1.3.</td>
<td>E3, ethanol</td>
</tr>
<tr>
<td>VOC</td>
<td>87 g</td>
<td>Recalculated, see Section 5.1.3.</td>
<td>E3, NMVOC</td>
</tr>
</tbody>
</table>

Table 45: Electricity use per 1 m² of DCB (area on one side defines the throughput – not total surface area) for the chip attachment with vacuum vapor-phase diffusion soldering.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>24 kWh</td>
<td>See Section 5.1.3.</td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>

Table 46: Electricity and flow gas use per 1 m² of baseplate (area on one side defines the throughput – not total surface area) for system soldering, i.e. joining the DCB and the baseplate, and the DCB to the contacts of the power terminals, with forced convection reflow soldering.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>24 kWh</td>
<td>See Section 5.1.3.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>64 kg</td>
<td>See Section 5.1.3.</td>
<td>E3, nitrogen, liquid</td>
</tr>
</tbody>
</table>

5.5.6 Mounting the frame and potting

The frame arrives to the assembly line with contacts and terminals ready-made, including nickel and gold in different layers, as well as pre-mounted and casted into the structure (Olszewski, 2006, Volke and Hornkamp, 2012). It is attached to the baseplate using screws and a thin layer of silicone adhesive serving as glue. The screws are secured from beneath through holes in the baseplate and into the frame. Next, the module moves on to the cleaning before the wire bonding process, described in Section 5.5.7, see Figure 26.

After the wire bonding, the module is filled with silicone potting gel and cured. Silicones are both tough and have a high degree of elasticity (Volke and Hornkamp, 2012). Some can be cured at room temperature, but thermal ovens, microwaves ovens or UV light are used to speed up the process (Coombs, 2008, Licari and Swanson, 2011). Also, some types of silicones can release gas during thermal curing leading contamination of nearby surfaces (Licari and Swanson, 2011). Outgassing should preferably be avoided. Therefore, UV light curing is beneficial since it can be made selectively for the transferred energy, matching the silicone composition, while other parts do not react to the energy transfer or can be shadowed, if necessary. UV lamp
intensities are in the range of 40-150 mW/cm² and the curing is rapid for the higher intensities (Licari and Swanson, 2011, Henkel, 2010, Wacker, 2014).

Finally, in the last step, silicone adhesive is used again to glue the lid onto the frame and seal the power module before it is transported to the inverter assembly. Depending on the selection of adhesive it can be cured at room temperature or with thermal curing.

Data collection

The silicones applied, both for gluing and potting, can be expected to be dispensed automatically (Licari and Swanson, 2011). Additionally, it was found reasonable that the screw mounting of the frame would be combined with a one-component room curing silicone adhesive recommended for sealing lids in high-volume manufacturing and automotive electronics applications (Henkel, 2011a, 2016). It was also assumed that screws are mounted by hand-held tools and that the same adhesive would be used again to attach the lid, in combination with some simple solution for the application of pressure, for example by stacking units with a weight on top, since the modules are left to cure for 24 hours (Henkel, 2016), presumably during intermediate storage. 50% of the adhesive use was ascribed to securing the frame, and the other 50% for the lid.

Data was gathered for the dispensing of the silicone gel (MTA, 2014, Wacker, 2014) and for UV curing (Henkel, 2011b, 2010, Wacker, 2014). It was found that energy for automatic dispensing of silicone gel is 0.3 kWh/kg. The corresponding value for the dispensing of the adhesive was found to be negligible. Additionally, it was established that the amount of gel in the module correlates very well with the DCB area, i.e. the gel thickness is constant. This also implies that the curing time using UV is the same regardless of the power module size, about 2 minutes (Wacker, 2014). Consequently, the energy use for UV curing of the potting gel was calculated to a constant value of 0.03 kWh for all power module sizes.

5.5.7 Bonding of wires and terminals

The wires interconnecting the upper side of the chips with the DCB conducting pattern can be bonded in a number of different ways. The same is true for the bonding of the DCB with the contacts for the auxiliary and power terminals. Ultrasonic wedge bonding is a friction based micro-welding technique based on ultrasound commonly used for aluminum wires, but it can also be adopted for copper to copper bonding with heavier wires or terminal contacts, sometimes referred to as ultrasonic welding (Volke and Hornkamp, 2012).

Wire and contact bonding may also be achieved with solder. However, a benefit of the ultrasonic method is that very little heat is transferred into the parts being welded which makes it suitable to use with terminals which have been pre-anchored into molded plastic frame (Blackwell, 2000, Volke and Hornkamp, 2012). The number of bond wires used for the contacting of the DCB to each chip depends on the current and the dimensions of the wires. Copper wires are commonly 100-500 μm in diameter (Volke and Hornkamp, 2012) and about 20% of the chip area can be wire-bonded (Grasshoff and Helldörfer, 2013).

Data collection

An estimation of the energy required for wire bonding was based on ultrasonic welding. After an inspection of photos showing open power modules (Olszewski, 2006, Volke and Hornkamp, 2012), it was estimated that roughly half the surface area of a wire creates a bond over a distance of 1-2 mm. With 20% of the chip area is bonded, this results in a span of about 20-80 bonds per cm² per active chip area, depending on the copper wire diameter (which is 500 μm for the lower end and 100 μm for the upper end). For example, assuming that the 80 kWh the reference power module would consist of one large IGBT chip and one diode chip in each leg of the six bridge topology, this summarizes to about 10 bonds of 500 μm copper wire per chip with an average bond length of 1.5 mm. Each wire bonded to a chip also has a bond to the DCB. From the photo inspection it was also noted that the power terminal connections either had a similar amount of bond wires of the same size as on the chip, or fewer but larger wires or contacts. The auxiliary terminals have fewer wires and smaller contacts. However, there are also bond wires interconnecting different conductors in the DBC pattern (or connecting different DCBs when there are several smaller substrates are used in the same unit). Overall, it was concluded that the total chip area is the best available model parameter to estimate the work to create all bonds. And the total number of bonds on the board was estimated to be 3-5 times higher compared to those on the chip only (or instead increasing in size), i.e. the total ultrasonically bonded area is roughly 60-100% of the total chip area.

41 In other sources, the terms “ultrasonic wedge bonding” and “ultrasonic welding” are used interchangeably, for example in Levine (2000).
Consequently, it was assumed that an area equal to the total chip area is bonded in each module. Moreover, a typical speed limit for ultrasonic wedge bonderers is six bonds per second according to Levine (2000, 2016), including wire feed and cutting. The rated power consumption of a modern ultrasonic welding machine capable of bonding 100-500 µm copper wires was acquired from Orthodyne (2012) and used to account both for both productive and non-productive operating time (the actual power draw during operation can be expected to be lower than the rated). The capacity stated by Levine (2000, 2016) was expected to be valid for smallest wire size. The final estimate came to 0.02 kWh/cm² of chip area in the module, indicating that the bonding of wires and terminals is a minor contributor the energy use in the power module assembly.

5.5.8 Cleaning steps in the power module assembly

According to Sheng and Colino (2005), the three most important cleaning steps in the power module assembly are carried out on the DCB and baseplate before soldering, on the joined unit after soldering, and on the module before the ultrasonic wedge bonding. The IGBT and power diode chips do not require cleaning since they are produced and packed in a cleanroom, and then mounted automatically just before the diffusion soldering process.

In pre-solder cleaning, ultrasonic aqueous cleaning can be used. Most important is a vacuum furnace bake at 150°C for at least 4 hours to ensure that all surfaces are clean and dry surface before the soldering processes (Sheng and Colino, 2005). The vacuum should be held at least at 50 µm Hg (6.6×10⁻² mbar)

The primary purpose with the post-solder cleaning is to remove flux. Consequently, the need for this cleaning step decreases when no-clean flux is used in the solder paste. On the other hand, cleaning is also important in preparation of securing the plastic frame onto the baseplate (Licari and Swanson, 2011). It is common to use solvents for this step and let the parts dry by evaporation (Sheng and Colino, 2005).

In the pre-wire-bond cleaning, the module is plasma cleaned (Sheng and Colino, 2005). It is placed in a container with low pressure argon gas and radio frequency voltages are used to ionize the gas, from 2-15 minutes (Sheng and Colino, 2005, Guan et al., 2004).

Data collection

For the pre-solder cleaning, the data gathered for the DCB bonding process was used and modified (see Section 5.5.3). The final step for in the cleaning of copper foils data from Ning et al. (2003) was re-used, were parts are processed ultrasonically for 10 minutes in a bath of deionized water with cleaning alcohol. The electricity consumption, tank size and capacity of the equipment was calculated using data from Unger and Landis (2014).

Similarly, for the vacuum bake procedure (i.e. the second activity of the pre-solder cleaning procedure), the simple furnace model based on data from Franz and Weilguni (2011), presented in Section 5.5.3, was used again in a rework to one constant heating zone of 150°C and operation during 4 hours. To match the desired vacuum requirement, the vacuum pump data was based on the Drystar 80 model by Edwards (2014), which specifies a 3.6 kW power draw to hold 3x10⁻² mbar, meeting the vacuum requirement by a good margin. The energy use for the ultrasonic cleaning step was found very small compared to vacuum bake step, and included in the rounded figure for the furnace energy use. The summarized dataset for the pre-solder cleaning step is presented in tables 47 and 48, equally applicable for the DCB and the baseplate.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity, furnace</td>
<td>31 kWh</td>
<td>Est. from Franz and Weilguni (2011)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity, ventilation</td>
<td>14 kWh</td>
<td>Adapted from Aros data, see 5.1.3.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Deionized water</td>
<td>90 g</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>110 g</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>E3, isopropanol</td>
</tr>
</tbody>
</table>

Table 47: Process input per 1 m² of DCB or baseplate (area on one side) for pre-solder cleaning.

<table>
<thead>
<tr>
<th>Liquid waste</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste solvents, conc. share of dilution</td>
<td>110 g</td>
<td>Calculated</td>
<td>E3, spent solvent mixture</td>
</tr>
</tbody>
</table>

Table 48: Waste per 1 m² of DCB or baseplate (area on one side) for pre-solder cleaning.
In the post-solder cleaning step it was assumed that the unit, now consisting of the DCB and baseplate in one piece, is dipped in a bath of isopropanol and acetone, and then left to dry in air. Again, the data gathered for the cleaning steps during the direct copper bonding procedure (see Section 5.5.3) was used for the estimation of solvent use. Bath losses due to drag-out and emissions to air during drying were assumed to be negligible, such that all input solvent becomes waste when the bath is replaced. Tables 49 and 50 report the data for the post-solder cleaning.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetone</td>
<td>90 g</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>E3, acetone, liquid</td>
</tr>
<tr>
<td>Isopropanol</td>
<td>90 g</td>
<td>Ning et al. (2003), TM (2010)</td>
<td>E3, isopropanol</td>
</tr>
</tbody>
</table>

Table 49: Process input per 1 m² of baseplate (area on one side) for post-solder cleaning.

<table>
<thead>
<tr>
<th>Solid waste</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste solvents, conc. share of dilution</td>
<td>110 g</td>
<td>Calculated</td>
<td>E3, spent solvent mixture</td>
</tr>
</tbody>
</table>

Table 50: Waste per 1 m² of baseplate (area on one side) for post-solder cleaning.

Finally, the pre-wire-bond plasma cleaning was modelled using data for batch cleaning equipment from Nordson MARCH (2015a, 2015b). For the large batch machine, it was assumed that two modules can be cleaned per electrode pair and for the small unit one module per electrode pair, based on the geometries of the chambers and the corresponding electrodes (Nordson MARCH, 2015a, b).

Vacuum is drawn using a pump before argon is carefully released into the chamber to establish a desired pressure. Again, the data from Edwards (2014) for the Drystar 80 model was found representative for the vacuum pump and the argon pressure was modelled at 120 mTorr (16 bar), in accordance with typical settings for pre-wire-bond cleaning (Getty et al., 2016, Guan et al., 2004). The cleaning time was chosen to be 10 minutes based on Sheng and Colino (2005) and Guan et al. (2004).

The amount of argon used and the energy consumptions per module were found to be very small – 140 mg and 50 Wh per unit – and possible to disregard in the compilation of the manufacturing inventory.

5.6 Assembly and building services

5.6.1 Mounting parts into a complete unit

In the last step of inverter production, all parts are assembled into a complete unit. The power module is screw mounted into the heatsink (in turn an integrated part of the casing) after application of the TIM on the heatsink surface (i.e. the same as the bottom of the housing compartment). Cable glands are screwed into threaded holes of the casing wall and the DC link capacitor is also secured inside the housing compartment. The laminated bus bar is screwed onto the terminals of the power module, the DC link capacitor and the cable glands to establish the high voltage circuit of the inverter unit.

Moreover, the external connector is attached to the logic board as well as mounted into the casing wall with the outer gasket acting as protection over any gap that might occur between the connector and the wall. The logic and driver boards are simultaneously mounted over the power stage parts such that all signal connections can be properly joined. Lastly, the casing lid is secured using screws to close to the housing compartment.

At this stage, programmable selective soldering is suitable for mounting and connecting through-hole devices in these assemblies, typically connectors or other components which are incompatible with reflow, for example due to thermal restrictions (Klenke, 2003). This technique has the advantage of a very precise contact time for each created solder joint and that component thermal exposure and flux residues on the PCB becomes limited since both flux and solder only are applied on specific locations (Klenke, 2003)

Data collection

The data representation of the final assembly procedure consists of the unit process for selective soldering of the external signal connector to the logic board, which is expected to take place first among different
assembly processes. All other steps, including the application of TIM and screw mounting of parts has been are conducted using handheld or small stationary tools, whose operation has been included under building services in terms of electricity use. The auxiliary signal connections of the power module and the interconnections between the two PCBs was modelled with press in pin board connectors, in line with the component classification reported in sections 4.1.4 and 4.1.5 (see appendices A and B for more details). Consequently, instead of soldering, these connections are established using a small press.

For the through hole mounted external connector, it was found to require a board area of 7 cm² with an average of 429 g/m² for the amount of applied solder. Selective soldering, in the same way as wave soldering, use bar solder and flux is sprayed on separately. Data for selective soldering was gathered from Aros (2013, 2014b, c, d, e, f, g), with solder losses estimated to 3% (Klenke, 2003). The flux consist of 5%, dicarboxylic acid and 95%, deionized water (Interflux, 2009). The water and some acid evaporates in the soldering process. Other acid remains on the board as a salt, but given the “no-clean flux” characteristics it was assumed unnecessary to wipe off.

The unit process data for selective soldering and the results for mounting the external connector to the reference logic board is reported in Table 51 and Table 52. As shown, the contribution of this step is practically negligible due to the relatively small size of only one connector.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount Per m²</th>
<th>Ref. PCB</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder bar, lead free¹</td>
<td>442 g</td>
<td>0.31 g</td>
<td>Aros (2013), (2014b, c, d, e, f, g)</td>
<td>E3, solder, bar, Sn95.5Ag3.9Cu0.6, for electr. ind.</td>
</tr>
<tr>
<td>Flux, aqueous, dicarboxylic acid share</td>
<td>10 g</td>
<td>7 mg</td>
<td>Interflux (2009), (Klenke, 2003)</td>
<td>E3, adipic acid</td>
</tr>
<tr>
<td>Flux, aqueous, deionized water share</td>
<td>180 g</td>
<td>130 mg</td>
<td></td>
<td>E3, water, deionised, from tap water, at user</td>
</tr>
<tr>
<td>Electricity</td>
<td>72.4 kWh</td>
<td>0.05 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>21 kg</td>
<td>15 g</td>
<td></td>
<td>E3, nitrogen, liquid</td>
</tr>
</tbody>
</table>

Note 1: The value for the amount of bar solder required for the reference PCB is based on the rounded, assumed amount on the board.

Table 51: Process input per 1 m² of employed printed circuit board area, and the result for the connector mounted on the reference PCB, for mounting the external connector to the logic board using selective soldering of lead free bar solder.

<table>
<thead>
<tr>
<th>Waste</th>
<th>Amount Per m²</th>
<th>Ref. PCB</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder waste¹</td>
<td>13 g</td>
<td>0.01 g</td>
<td>Calculated</td>
<td>Solder waste, optional recycling</td>
</tr>
</tbody>
</table>

Note 1: The value for solder waste for the reference PCB is based on the rounded, assumed amount on the board. See note 1 above.

Table 52: Waste per 1 m² of employed printed circuit board area, and the result for the connector mounted on the reference PCB, for mounting the external connector to the logic board using selective soldering of lead free bar solder.

5.6.2 Technical building services

Additional to the specific manufacturing processes presented so far in Chapter 5, there are also several basic functions which are necessary in order to operate an electronics factory, referred to as technical building services. Maintaining these services in operation requires energy, and may cause emissions. However, unlike the specific production processes, this environmental load does not have a direct physical link to each unit produced, e.g. no amount of mass being removed or reshaped, and no parts are joined together. Instead, the energy used relates to the total activity and size of the factory, and the burden carried by each inverter unit must be decided by means of allocation.

Technical building services include heating, ventilation, and lighting, for example. Moreover, computers for control of the machinery and for testing, are also necessary. Some machines require start up procedures and energy to hold them at standby. In cold climates, such as Sweden, heating may constitute a significant share of the energy consumption whereas in other countries, air-cooling systems may be more important. Anyhow, both external factors such as the local climate, and process specific conditions governed by the
product design and coupled required machinery, determine the need for various technical building services (Bonvoisin et al., 2013). Often there is a substantial energy demand for these services, e.g. to start-up and maintain the equipment ready to operate (Gutowski et al., 2006). In fact, it is common that non-productive machine time, computer use and other technical building services constitute the major share of the total factory energy consumption (Bonvoisin et al., 2013).

The compressed air system typically belongs to the technical building services. As mentioned in previous sections, it is used in machines based on pneumatic force, in spray and blow applications, and also for pneumatic control of machinery. In pneumatic control, actuators are used to control the movement or positioning of a workpiece or a sensor on a machine. Compressed air systems generally suffer both from large heat losses from the compressor and large leakage losses (U.S. Department of Energy, 2003). Proactive detection and mending of leaks can considerably reduce the energy used by the compressed air system.

Finally, building services can include more than energy use, for example the use of chemicals in general cleaning activities.

Data collection
First, data for building services was collected from Aros Electronics AB for the PCB assembly (Aros, 2013, 2014a, b, c, d, e, f, g, Edgren, 2014, 2015, 2017, Welin, 2014a, b). Occupied floor area was used as a basis for allocation to separate the PCB assembly operation of the production facility (estimated to 70%) building services supporting the inverter unit assembly (estimated to 30%) (Edgren, 2017). At Aros, the production site (unlike the office building, which is not included here) is self-sufficient in heat generation all year despite Swedish climate, due to heat dissipation from the many large ovens (Edgren, 2017). Therefore, no heating is included and the building services for the PCB assembly were divided into three categories for different types of electricity use: compressed air, basic ventilation and cooling, and general electricity and machinery. The last category include computers (production was assumed to account for 20% of all computers, with the remaining 80% in laboratories and offices), general machinery and tools, machine stand-by operation, test stations and lighting. Data was summarized for yearly operation and the divided by the total amount of board area mounted per year at the plant, to receive the figures stated in Table 53.

General cleaning of boards and machines was found to consume very small amount of solvents, in total 16 kg per year for the whole plant. Split into the main constituents and stated per square meter of board area, it was calculated to 1 g/m² of isopropanol, 1 g/m² of ethanol and 0.7 g/m² of methanol. These resulting values were found negligible, and were not included in the overall compilation.

Next, the Aros data was used to calculate the building services for the section of the production site where complete inverter units are assembled. Here it was noted that about 50% of all assembled PCBs continues within the factory to be mounted into casings and assembled in complete inverter units at Aros (Edgren, 2017) (or complete units of other power electronic applications) while remaining PCBs are either shipped to a sister company in the same group (30%), or are delivered directly to customers (20%). Consequently, the reported overall number of mounted PCBs where used to decide the number of internally assembled inverter units at the facility and this figure was used to calculate the average building services’ energy per unit going through final inverter assembly. Noteworthy, all use of pneumatics was linked to the machines used in the PCB assembly and therefore excluded for the inverter unit summary. Table 54 shows the results and as can be noted, the order of magnitude is smaller when data is expressed per piece rather than square meters.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for compressed air (pneumatic control)</td>
<td>23 kWh</td>
<td>Aros (2013, 2014a, b, c, d, e, f, g), Edgren (2014, 2015, 2017), Welin (2014a, 2014b)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity for ventilation and cooling</td>
<td>17 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>General electricity and machinery</td>
<td>21 kWh</td>
<td>Welin (2014a, 2014b)</td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>

Table 53: Electricity input per m² of PCB for different types of technical building services.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per piece</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for ventilation and cooling</td>
<td>0.3 kWh</td>
<td>Aros (2013, 2014a, b, c, d, e, f, g), Edgren (2014, 2015, 2017), Welin (2014a, 2014b)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>General electricity and machinery</td>
<td>0.3 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>

Table 54: Electricity input per inverter unit (piece) for different types of technical building services.
Next, the data compiled for the PCB assembly was used to approximate the electricity used for building services also in the DCB production and the assembly of the power module, i.e. the fabrication steps presented in section 5.5 except for the making of the ceramic substrate (where buildings services already were included, see section 5.5.2). The approximation was made by comparing the number of identified process steps in the DCB production and module assembly (in total 23 steps when excluding the ceramic substrate factory, see Figure 25 and Figure 26) to the number of steps in the PCB assembly (6 steps, see Figure 17), and scale the results accordingly. Building services expressed per square meter of DCB is reported in Table 55.

Finally, data for building services were also included for the machining, cleaning and painting (or anodizing) of the casing. Upstream, the casting process already include building services, whereas the following steps in the handling of the casing do not. In this case, the data was estimated from the building services reported for electrical motors by Nordelöf et al. (2017) (per piece) based on a similar scaling as used for the DCBs compared to PCBs (the casing handling included 3 steps compared to 19 in the electric motor factory). The motivation for using this data is that production of motors include similar steps, i.e. machining, cleaning and painting of motor housings. The resulting estimation for building services for the casing production is reported in Table 56.

### Table 55: Electricity input per m² of DCB for different types of technical building services.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per m²</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for compressed air (pneumatic control)</td>
<td>88 kWh</td>
<td>Scaled from Table 53, see text.</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity for ventilation and cooling</td>
<td>65 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>General electricity and machinery</td>
<td>80 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>

### Table 56: Electricity input per piece for different types of technical building services during machining, cleaning and painting or anodizing of casings for inverter units.

<table>
<thead>
<tr>
<th>Process input</th>
<th>Amount per piece</th>
<th>Source</th>
<th>Linked flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for compressed air (pneumatic control)</td>
<td>0.1 kWh</td>
<td>Nordelöf et al. (2017)</td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity for heating (heat pumps), yearly average</td>
<td>0.6 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>Electricity for ventilation</td>
<td>0.5 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
<tr>
<td>General electricity and machinery</td>
<td>0.3 kWh</td>
<td></td>
<td>Electricity, optional</td>
</tr>
</tbody>
</table>
References


Gast (2012). *Rotary Vane Compressors and Vacuum Pumps*. Benton Harbor, Michigan, USA: Gast Manufacturing Inc. (Sales brochure, doc. no. F-5 (01-12)).


Welin, P. (2014a). Mätning/appskattning av årselförbrukningen 2012-2013 vid Aros Electronics AB. 3 September. Aros Electronics AB. (Data from supplier's online electricity consumption charts, broken down and complemented with machine data, for the energy and power use at Aros Electronics AB).

Welin, P. (2014b). Mätning/appskattning av årselförbrukningen 2014 vid Aros Electronics AB. 17 November. Aros Electronics AB. (Data from supplier's online electricity consumption charts, broken down and complemented with machine data, for the energy and power use at Aros Electronics AB).


Appendix A: Driver board component classification

All components on the large reference driver board were classified into different types as defined in the Ecoinvent database (Hischier et al., 2007, Weidema et al., 2013), and estimated in mass based on the package codes specified in the bill of materials of the large reference unit (Infineon, 2014b). Additional mass data was collected for identical or similar components, i.e. with the same or comparable size. Conversion tables were used to identify equivalent codes in different standards (Topline, 2016).

The nominal package mass was used in most cases. However, the Ecoinvent value for the average mass of a specific component type was used when no specific package code was given by the bill of materials. For example, in the case of the transformer, which is the largest component on the board, several PCB transformers of representative size were compared and all were found to weigh within a range of 20–40 grams. Hence, the typical mass of 30 grams specified by Hischier et al. (2007), was used. The connectors to the auxiliary terminals of the power module were also identified to be large components on the board. The specification of the original supplier (JST, 2012) states the size but not the mass. Instead, these connectors were assumed to have a similar composition as another board connector type (Elfa, 2016). Data for the latter was collected and the mass data was scaled based on the volume difference, to give a final mass estimation of the original connector.

Lastly, for the component type classification, it should be mentioned that the matching of each component with the Ecoinvent type categories, are approximations in terms of in depth structure. Still, the level of data detail was judged to be well suited for the overall purpose of the LCI model. Summarizing, total number of driver board components came to 316 and their total estimated mass to 65 grams. The corresponding mass, if the typical average component masses stated in Ecoinvent had been used instead, came to 156 grams. The board area was calculated to 1.5 dm². An overview of the compilation is shown in the table below. In this table, the component type names follow the nomenclature of Hischier et al. (2007), as used in Ecoinvent 2. The corresponding names for Ecoinvent 3 database (Weidema et al., 2013), are presented in Table 4, in Section 4.1.4 of the report.

<table>
<thead>
<tr>
<th>Ecoinvent</th>
<th>Infineon (2014b) bill of materials</th>
<th>Mass data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component type</td>
<td>Average mass per unit</td>
<td>Device code</td>
</tr>
<tr>
<td>Capacitor, small electrolyte</td>
<td>1.29 g</td>
<td>22u/63V</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4u7/25V/X7R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/50V/X7R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22n/50V/X7R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10u/16V/X7R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/16V/X7R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150p/50V/C0G</td>
</tr>
<tr>
<td></td>
<td></td>
<td>330p/50V/C0G</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10n/50V/X7R</td>
</tr>
<tr>
<td>Capacitor, SMD type</td>
<td>86 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4u7/50V/X7R</td>
<td>C1210</td>
</tr>
<tr>
<td></td>
<td>100nF/100V/X7R</td>
<td>C1206</td>
</tr>
<tr>
<td></td>
<td>22n/50V/X7R</td>
<td>C0402</td>
</tr>
<tr>
<td></td>
<td>22u/16V/X7R</td>
<td>C1210</td>
</tr>
<tr>
<td></td>
<td>10n/50V/X7R</td>
<td>C0603</td>
</tr>
<tr>
<td></td>
<td>100n/50V/X7R</td>
<td>C0805</td>
</tr>
<tr>
<td></td>
<td>100pF/100V/C0G</td>
<td>C0603</td>
</tr>
<tr>
<td>Component type</td>
<td>Average mass per unit</td>
<td>Device code</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Capacitor, SMD type</td>
<td>86 mg</td>
<td>10n/50V/X7R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1u/16V/X7R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1u/16V/V7R</td>
</tr>
<tr>
<td>Capacitor, tantalum</td>
<td>254 mg</td>
<td>22u/35V</td>
</tr>
<tr>
<td>Connector, clamp type</td>
<td>9.0 g</td>
<td>MMS-112-01-L-DV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JST 09HVD6B</td>
</tr>
<tr>
<td>Diode, LED</td>
<td>350 mg</td>
<td>LED_LSM676-MQ</td>
</tr>
<tr>
<td>Diode, SMD type</td>
<td>32 mg</td>
<td>P6SMBS110A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ES1A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ES1D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1SMA5929B3T3G</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MURA160T3G</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SMBJ14CA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1SMB5935B3T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8ZV55/C13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1SMB30AT3</td>
</tr>
<tr>
<td>IC, logic type</td>
<td>2.6 g</td>
<td>ACPL-782T</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1ED02012-FA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AD8552ARZ</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LM3478MM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TLE4296GV50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>74LV1G11GW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MAX6457UKD3A-T</td>
</tr>
<tr>
<td>Inductor, min. RF chip type</td>
<td>17 mg</td>
<td>MURATA_BLM21P</td>
</tr>
<tr>
<td>Resistor, SMD type</td>
<td>10 mg</td>
<td>OR</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4K7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>47R</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2R7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4K75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2K/0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4K / 0.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>590K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3K9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10K 0.1%</td>
</tr>
</tbody>
</table>
Continued from previous page

<table>
<thead>
<tr>
<th>Component type</th>
<th>Average mass per unit</th>
<th>Ecoinvent</th>
<th>Infineon (2014b) bill of materials</th>
<th>Mass data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistor, SMD type</td>
<td>10 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1k6</td>
<td>R1206</td>
<td>18</td>
<td>10 mg</td>
<td>180 mg</td>
</tr>
<tr>
<td>80K6</td>
<td>R0402</td>
<td>1</td>
<td>0.8 mg</td>
<td>0.8 mg</td>
</tr>
<tr>
<td>19K6</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
</tr>
<tr>
<td>0R025</td>
<td>R2010</td>
<td>1</td>
<td>27 mg</td>
<td>27 mg</td>
</tr>
<tr>
<td>0R</td>
<td>R1210</td>
<td>2</td>
<td>16 mg</td>
<td>32 mg</td>
</tr>
<tr>
<td>59K</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
</tr>
<tr>
<td>10K/1%</td>
<td>R0603</td>
<td>6</td>
<td>2 mg</td>
<td>12 mg</td>
</tr>
<tr>
<td>opt</td>
<td>R0603</td>
<td>3</td>
<td>2 mg</td>
<td>6 mg</td>
</tr>
<tr>
<td>158R</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
</tr>
<tr>
<td>39R</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
</tr>
<tr>
<td>15K</td>
<td>R0603</td>
<td>9</td>
<td>2 mg</td>
<td>18 mg</td>
</tr>
<tr>
<td>1K</td>
<td>R0603</td>
<td>3</td>
<td>2 mg</td>
<td>6 mg</td>
</tr>
<tr>
<td>220R</td>
<td>R0603</td>
<td>3</td>
<td>2 mg</td>
<td>6 mg</td>
</tr>
<tr>
<td>100R</td>
<td>R0603</td>
<td>6</td>
<td>2 mg</td>
<td>12 mg</td>
</tr>
<tr>
<td>opt</td>
<td>R1210</td>
<td>1</td>
<td>16 mg</td>
<td>16 mg</td>
</tr>
<tr>
<td>226K</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
</tr>
<tr>
<td>5K1</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
</tr>
<tr>
<td>47K</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
</tr>
<tr>
<td>Transformer, low voltage</td>
<td>30.0 g</td>
<td>TRANSFORMER2</td>
<td>1</td>
<td>30.0 g</td>
</tr>
<tr>
<td>Transistor, SMD type</td>
<td>593 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPD144N06NG</td>
<td>TO252</td>
<td>1</td>
<td>357 mg</td>
<td>357 mg</td>
</tr>
<tr>
<td>IPD90P03P4L-04</td>
<td>TO252</td>
<td>1</td>
<td>357 mg</td>
<td>357 mg</td>
</tr>
<tr>
<td>ZXTN2010Z</td>
<td>SOT89</td>
<td>6</td>
<td>51 mg</td>
<td>306 mg</td>
</tr>
<tr>
<td>ZXT2012Z</td>
<td>SOT89</td>
<td>6</td>
<td>51 mg</td>
<td>306 mg</td>
</tr>
<tr>
<td>BCR183S</td>
<td>SOT363</td>
<td>2</td>
<td>6 mg</td>
<td>12 mg</td>
</tr>
<tr>
<td>BCR10PN</td>
<td>SOT363</td>
<td>1</td>
<td>6 mg</td>
<td>6 mg</td>
</tr>
</tbody>
</table>

Ecoinvent
Infineon (2014b)
Mass data

Bill of materials
Specific mass per unit
Total mass
Mass reference
Appendix B: Logic board component classification

All components on the large reference logic board were classified into different types as defined in the Ecoinvent database (Hischier et al., 2007, Weidema et al., 2013), and estimated in mass based on the package codes specified in the bill of materials of the large reference unit (Infineon, 2014b). Additional mass data was collected for identical or similar components, i.e. with the same or comparable size. Conversion tables were used to identify equivalent codes in different standards (Topline, 2016).

The nominal package mass was used in most cases. For the component type classification, it should be mentioned that the matching of each component with the Ecoinvent type categories, are approximations in terms of in depth structure. Still, the level of data detail was judged to be well suited for the overall purpose of the LCI model. Summarizing, total number of logic board components came to 457 and their total estimated mass to 28 grams. The corresponding mass, if the typical average component masses stated in Ecoinvent had been used instead, came to 251 grams. The board area was calculated to 0.7 dm². An overview of the compilation is shown in the table below. In this table, the component type names follow the nomenclature of Hischier et al. (2007), as used in Ecoinvent 2. The corresponding names for Ecoinvent 3 database (Weidema et al., 2013), are presented in Table 5, in Section 4.1.5 of the report.

<table>
<thead>
<tr>
<th>Component type</th>
<th>Average mass per unit</th>
<th>Device code</th>
<th>EIA package code.</th>
<th>Number of SMDs</th>
<th>Specific mass per unit</th>
<th>Total mass</th>
<th>Mass reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor, small electrolyte</td>
<td>1.29 g</td>
<td>330µF/35V/EMVE</td>
<td>C1010</td>
<td>2</td>
<td>1.83 g</td>
<td>3.66 g</td>
<td>Nic Components (2000)</td>
</tr>
<tr>
<td>Capacitor, SMD type</td>
<td>86 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TDK (2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/16V/COG</td>
<td>C0402</td>
<td>4</td>
<td>1.25 mg</td>
<td>5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>330p/16V/X7R</td>
<td>C0402</td>
<td>4</td>
<td>1.25 mg</td>
<td>5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4µ7/16V/X7R</td>
<td>C1206</td>
<td>1</td>
<td>41 mg</td>
<td>41 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10n/16V/X7R</td>
<td>C0402</td>
<td>4</td>
<td>1.25 mg</td>
<td>5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10µF/10V/X7R</td>
<td>C1206</td>
<td>1</td>
<td>41 mg</td>
<td>41 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4µ7/25V/X7R</td>
<td>C1206</td>
<td>2</td>
<td>41 mg</td>
<td>82 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20pF/50V/COG</td>
<td>C0402</td>
<td>2</td>
<td>1.25 mg</td>
<td>2.5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/50V/X7R</td>
<td>C0603</td>
<td>8</td>
<td>5 mg</td>
<td>40 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>22µ/16V/X7R</td>
<td>C1210</td>
<td>5</td>
<td>80 mg</td>
<td>400 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>220nF/100V/X7R</td>
<td>C1206</td>
<td>1</td>
<td>41 mg</td>
<td>41 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.7n/25V/COG</td>
<td>C0402</td>
<td>2</td>
<td>1.25 mg</td>
<td>2.5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>22µ/16V/X7R</td>
<td>C1210</td>
<td>2</td>
<td>80 mg</td>
<td>160 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/25V/X7R</td>
<td>C0603</td>
<td>2</td>
<td>5 mg</td>
<td>10 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>47n/16V/X7R</td>
<td>C0402</td>
<td>1</td>
<td>1.25 mg</td>
<td>1.25 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1µ_X7R_10V</td>
<td>C0805</td>
<td>2</td>
<td>16 mg</td>
<td>32 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1n/50V/X7R</td>
<td>C0402</td>
<td>14</td>
<td>1.25 mg</td>
<td>17.5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100p/50V/X7R</td>
<td>C0603</td>
<td>2</td>
<td>5 mg</td>
<td>35 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>330p_COG_50V</td>
<td>C0603</td>
<td>3</td>
<td>1.25 mg</td>
<td>3.75 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6800p/10V/COG</td>
<td>C0603</td>
<td>3</td>
<td>5 mg</td>
<td>15 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10p/50V/X7R</td>
<td>C0603</td>
<td>9</td>
<td>5 mg</td>
<td>45 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3300p/10V/COG</td>
<td>C0603</td>
<td>3</td>
<td>5 mg</td>
<td>15 mg</td>
<td></td>
</tr>
<tr>
<td>Component type</td>
<td>Average mass per unit</td>
<td>Device code</td>
<td>EIA package code.</td>
<td>Number of SMDs</td>
<td>Specific mass per unit</td>
<td>Total mass</td>
<td>Mass reference</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------</td>
<td>-------------</td>
<td>-------------------</td>
<td>---------------</td>
<td>------------------------</td>
<td>------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Capacitor, SMD type</td>
<td>86 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/16V/X7R</td>
<td>C0402</td>
<td>1</td>
<td>1.25 mg</td>
<td>1.25 mg</td>
<td>TDK (2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>opt</td>
<td>C0402</td>
<td>1</td>
<td>1.25 mg</td>
<td>1.25 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/50V/X7R</td>
<td>C0805</td>
<td>2</td>
<td>16 mg</td>
<td>32 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100n/16V/X7R</td>
<td>C0603</td>
<td>6</td>
<td>5 mg</td>
<td>30 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10p/16V/X7R</td>
<td>C0603</td>
<td>2</td>
<td>5 mg</td>
<td>10 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4u7/10V/X7R</td>
<td>C1210</td>
<td>1</td>
<td>80 mg</td>
<td>80 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4u7/10V/X7R</td>
<td>C1206</td>
<td>2</td>
<td>41 mg</td>
<td>82 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1u/25V/X7R</td>
<td>C0805</td>
<td>2</td>
<td>16 mg</td>
<td>32 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>680n/50V</td>
<td>C1206</td>
<td>1</td>
<td>41 mg</td>
<td>41 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>220n/25V/X7R</td>
<td>C0603</td>
<td>1</td>
<td>5 mg</td>
<td>5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10u/10V/X7R</td>
<td>C1206</td>
<td>1</td>
<td>41 mg</td>
<td>41 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1n/16V/X7R</td>
<td>C0402</td>
<td>1</td>
<td>1.25 mg</td>
<td>1.25 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.7u/50V/X7R</td>
<td>C1210</td>
<td>1</td>
<td>80 mg</td>
<td>80 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1n/50V/X7R_opt</td>
<td>C0402</td>
<td>16</td>
<td>1.25 mg</td>
<td>20 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100nF_C0G_50V</td>
<td>C0603</td>
<td>1</td>
<td>5 mg</td>
<td>5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>470pF_C0G_50V</td>
<td>C0603</td>
<td>2</td>
<td>5 mg</td>
<td>10 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10pF_C0G_50V</td>
<td>C0402</td>
<td>2</td>
<td>1.25 mg</td>
<td>2.5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20pF_C0G_50V</td>
<td>C0603</td>
<td>4</td>
<td>5 mg</td>
<td>20 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>22uF_X7R_10V</td>
<td>C1206</td>
<td>2</td>
<td>41 mg</td>
<td>82 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10uF_X7R_10V</td>
<td>C0805</td>
<td>2</td>
<td>16 mg</td>
<td>32 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>470nF_X7R_10V</td>
<td>C0603</td>
<td>2</td>
<td>5 mg</td>
<td>10 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100nF_X7R_10V</td>
<td>C0402</td>
<td>2</td>
<td>1.25 mg</td>
<td>2.5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5nF_C0G_10V</td>
<td>C0402</td>
<td>1</td>
<td>1.25 mg</td>
<td>1.25 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>100pF_X7R_10V</td>
<td>C0402</td>
<td>2</td>
<td>1.25 mg</td>
<td>2.5 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>opt</td>
<td>R0603</td>
<td>5</td>
<td>41 mg</td>
<td>205 mg</td>
<td></td>
</tr>
<tr>
<td>Connector, clamp type</td>
<td>9.0 g</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>TW-12-06-L-D</td>
<td>475-SM-A</td>
<td>1</td>
<td>1.52 g</td>
<td>1.52 g</td>
<td>Samtec (2014e)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TFM-110-02</td>
<td>S-S-WT</td>
<td>1</td>
<td>320 mg</td>
<td>320 mg</td>
<td>Samtec (2014d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MB80-5125042P</td>
<td>Harwin</td>
<td>1</td>
<td>3.0 g</td>
<td>3.0 g</td>
<td>Harwin (2012)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FTSH-105-01</td>
<td>XXX-DV-K</td>
<td>2</td>
<td>320 mg</td>
<td>640 mg</td>
<td>Samtec (2014a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HTST-108-01</td>
<td>XX-DV-P</td>
<td>1</td>
<td>2.35 g</td>
<td>2.35 g</td>
<td>Samtec (2014b)</td>
</tr>
<tr>
<td>Connector, switch, toggle type</td>
<td>29 g</td>
<td>2way</td>
<td>Jumper</td>
<td>2</td>
<td>112 mg</td>
<td>224 mg</td>
<td>Harwin (2011)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1-1571983-1</td>
<td>Tyco</td>
<td>1</td>
<td>79 mg</td>
<td>79 mg</td>
<td>TE Connectivity (2016)</td>
</tr>
<tr>
<td>Diode, SMD type</td>
<td>32 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBRSS340T3</td>
<td>SMC</td>
<td>1</td>
<td>217 mg</td>
<td>217 mg</td>
<td>ON Semiconductor (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BZV55/C13</td>
<td>SOD80C</td>
<td>1</td>
<td>64 mg</td>
<td>64 mg</td>
<td>Diodes Inc. (2014b)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1SMB30AT3</td>
<td>SMB</td>
<td>1</td>
<td>93 mg</td>
<td>93 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SS12_1A_if_20V</td>
<td>SMA</td>
<td>2</td>
<td>64 mg</td>
<td>128 mg</td>
<td></td>
</tr>
<tr>
<td>Component type</td>
<td>Average mass per unit</td>
<td>Ecoinvent</td>
<td>Infineon (2014b) bill of materials</td>
<td>Mass data</td>
<td>Mass reference</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------</td>
<td>-----------------------</td>
<td>-----------</td>
<td>-------------------------------------</td>
<td>-----------</td>
<td>----------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode, SMD type</td>
<td>32 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAT54-04W</td>
<td>SOT323</td>
<td>3</td>
<td>6 mg</td>
<td>18 mg</td>
<td>Infineon (2013c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAS52-02V</td>
<td>SC79</td>
<td>4</td>
<td>2 mg</td>
<td>8 mg</td>
<td>Infineon (2013a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAS3010A-03W</td>
<td>SOD323</td>
<td>2</td>
<td>5 mg</td>
<td>10 mg</td>
<td>Infineon (2013b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode, LED</td>
<td>350 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LED_LSM676-MQ</td>
<td>TLMX2300</td>
<td>1</td>
<td>7 mg</td>
<td>7 mg</td>
<td>Osram (2013)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LED_SML-512MW</td>
<td>0603 GRN</td>
<td>2</td>
<td>2 mg</td>
<td>4 mg</td>
<td>Osram (2012b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC, logic type</td>
<td>2.6 g</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LT1639HS</td>
<td>SO14</td>
<td>1</td>
<td>133 mg</td>
<td>133 mg</td>
<td>Linear Tech. (2016)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLE7368-3E</td>
<td>SO36-38</td>
<td>1</td>
<td>730 mg</td>
<td>730 mg</td>
<td>Infineon (2013o)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETT5S-20.000M</td>
<td>EH2645</td>
<td>1</td>
<td>190 mg</td>
<td>190 mg</td>
<td>IPC (2008a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAX6369KA-T</td>
<td>SOT23-8</td>
<td>1</td>
<td>24 mg</td>
<td>24 mg</td>
<td>Zetex (2007d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAK-TC1767-256</td>
<td>LQFP176</td>
<td>1</td>
<td>2.02 g</td>
<td>2.02 g</td>
<td>Infineon (2015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLE4266GSV10</td>
<td>SOT223</td>
<td>1</td>
<td>110 mg</td>
<td>110 mg</td>
<td>Infineon (2013i)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS92LV010A</td>
<td>SO8</td>
<td>1</td>
<td>77 mg</td>
<td>77 mg</td>
<td>Fairchild (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74LVC2G04GW</td>
<td>SOT363</td>
<td>1</td>
<td>6 mg</td>
<td>6 mg</td>
<td>Diodes Inc. (2014a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74LVCH16T245DL</td>
<td>SSOP48</td>
<td>1</td>
<td>625 mg</td>
<td>625 mg</td>
<td>IPC (2008b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DS90LV031A</td>
<td>SO16-1</td>
<td>1</td>
<td>144 mg</td>
<td>144 mg</td>
<td>Fairchild (2000b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM26C32QD</td>
<td>SO16-1</td>
<td>1</td>
<td>144 mg</td>
<td>144 mg</td>
<td>Fairchild (2000b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAX6143AA5AS0</td>
<td>SO8</td>
<td>1</td>
<td>77 mg</td>
<td>77 mg</td>
<td>Fairchild (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM50CIM3</td>
<td>SOT23</td>
<td>1</td>
<td>8 mg</td>
<td>8 mg</td>
<td>Zetex (2007c)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLE7250G</td>
<td>SO8</td>
<td>1</td>
<td>77 mg</td>
<td>77 mg</td>
<td>Fairchild (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLE6251G</td>
<td>SO14</td>
<td>1</td>
<td>137 mg</td>
<td>137 mg</td>
<td>Infineon (2013n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LT1800CS5</td>
<td>SOT23-5</td>
<td>1</td>
<td>12 mg</td>
<td>12 mg</td>
<td>Zetex (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OPA2171AIDGK</td>
<td>SO8</td>
<td>1</td>
<td>77 mg</td>
<td>77 mg</td>
<td>Fairchild (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AD2S1210DSTZ</td>
<td>LQFP48</td>
<td>1</td>
<td>138 mg</td>
<td>138 mg</td>
<td>Analog Devices (2014)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAK-TC2777TU-64F</td>
<td>LFBGA-292</td>
<td>1</td>
<td>937 mg</td>
<td>937 mg</td>
<td>Infineon (2014d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LMV344IDR</td>
<td>SO14</td>
<td>1</td>
<td>129 mg</td>
<td>129 mg</td>
<td>Fairchild (2000a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TEC5S5QD</td>
<td>SO8</td>
<td>1</td>
<td>77 mg</td>
<td>77 mg</td>
<td>Fairchild (2005)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCX_AM-20MAGE</td>
<td>3.2x2.5</td>
<td></td>
<td>18 mg</td>
<td>18 mg</td>
<td>River Electec (2014)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.192MAJB-UT</td>
<td>HCM49</td>
<td>1</td>
<td>573 mg</td>
<td>573 mg</td>
<td>Citizen (2012)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAX3232EIPWRQ</td>
<td>TSSOP16</td>
<td>1</td>
<td>60 mg</td>
<td>60 mg</td>
<td>Infineon (2013k)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC, memory type</td>
<td>2.3 g</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AT25256A-10TQ</td>
<td>TSSOP8</td>
<td>1</td>
<td>36 mg</td>
<td>36 mg</td>
<td>AMTL (2016)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductor, min. RF chip type</td>
<td>17 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MURATA_BLM21G</td>
<td>L0805</td>
<td>10</td>
<td>35 mg</td>
<td>350 mg</td>
<td>Nic Components (2000)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductor, multilay. chip type</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4u7_CVH252009</td>
<td>L1008</td>
<td>1</td>
<td>18 mg</td>
<td>18 mg</td>
<td>Bourns (2011)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductor, ring core choke type</td>
<td>6.0 g</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EP2OS_104N001</td>
<td>BB2789C0</td>
<td>2</td>
<td>160 mg</td>
<td>320 mg</td>
<td>Epcos (2008)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WE_7447709470</td>
<td>PD744770</td>
<td>1</td>
<td>5.4 g</td>
<td>5.4 g</td>
<td>Würth Elektronik (2014)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistor, SMD type</td>
<td>10 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>opt</td>
<td>R0603</td>
<td>24</td>
<td>2 mg</td>
<td>48 mg</td>
<td>Panasonic (2008)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10K</td>
<td>R0402</td>
<td>38</td>
<td>0.8 mg</td>
<td>30.4 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15K</td>
<td>R0402</td>
<td>4</td>
<td>0.8 mg</td>
<td>3.2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1K</td>
<td>R0402</td>
<td>12</td>
<td>0.8 mg</td>
<td>9.6 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component type</td>
<td>Average mass per unit</td>
<td>Device code</td>
<td>EIA package code</td>
<td>Number of SMDs</td>
<td>Specific mass per unit</td>
<td>Total mass</td>
<td>Mass reference</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------</td>
<td>-------------</td>
<td>----------------</td>
<td>----------------</td>
<td>------------------------</td>
<td>-----------</td>
<td>----------------</td>
</tr>
<tr>
<td>Resistor, SMD type</td>
<td>10 mg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Panasonic (2008)</td>
</tr>
<tr>
<td>10K</td>
<td>R0603</td>
<td>15</td>
<td>2 mg</td>
<td>30 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMK-R000</td>
<td>R1206</td>
<td>1</td>
<td>10 mg</td>
<td>10 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6K8_TK100_0.1%</td>
<td>RO402</td>
<td>2</td>
<td>0.8 mg</td>
<td>1.6 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3K6/0.1%</td>
<td>R0603</td>
<td>2</td>
<td>2 mg</td>
<td>4 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0R_opt</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4K7</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220R</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>68K</td>
<td>R0402</td>
<td>5</td>
<td>0.8 mg</td>
<td>4 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51K</td>
<td>R0402</td>
<td>6</td>
<td>0.8 mg</td>
<td>4.8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6K8</td>
<td>R0402</td>
<td>6</td>
<td>0.8 mg</td>
<td>4.8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47K</td>
<td>R0402</td>
<td>3</td>
<td>0.8 mg</td>
<td>2.4 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1K_TK100_1%</td>
<td>R0402</td>
<td>3</td>
<td>0.8 mg</td>
<td>2.4 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100R</td>
<td>R0603</td>
<td>4</td>
<td>2 mg</td>
<td>8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0R</td>
<td>R0603</td>
<td>7</td>
<td>2 mg</td>
<td>14 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0R/0.1%</td>
<td>R0402</td>
<td>1</td>
<td>0.8 mg</td>
<td>0.8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270K</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1K</td>
<td>R0603</td>
<td>6</td>
<td>2 mg</td>
<td>12 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2K7</td>
<td>R0603</td>
<td>3</td>
<td>2 mg</td>
<td>6 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60R_TK100_1%</td>
<td>R0603</td>
<td>4</td>
<td>2 mg</td>
<td>8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10K_TK100_1%</td>
<td>R0603</td>
<td>4</td>
<td>2 mg</td>
<td>8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1K_TK100_1%</td>
<td>R0603</td>
<td>5</td>
<td>2 mg</td>
<td>10 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39K_TK100_1%</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0R_TK100_1%_opt</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10K_TK100_1%</td>
<td>R0402</td>
<td>1</td>
<td>0.8 mg</td>
<td>0.8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>51K</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47K_TK100_1%</td>
<td>R0603</td>
<td>4</td>
<td>2 mg</td>
<td>8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0R_TK100_1%</td>
<td>R0603</td>
<td>3</td>
<td>2 mg</td>
<td>6 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0R</td>
<td>R0402</td>
<td>2</td>
<td>0.8 mg</td>
<td>1.6 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1K5</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24K/0.1%</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2K4_TK100_1%</td>
<td>R0402</td>
<td>4</td>
<td>0.8 mg</td>
<td>3.2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11K5/0.1%</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4R7_TK100_1%</td>
<td>R0402</td>
<td>4</td>
<td>0.8 mg</td>
<td>3.2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5R6_TK100_1%</td>
<td>R0402</td>
<td>4</td>
<td>0.8 mg</td>
<td>3.2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0R_TK100_1%_opt</td>
<td>R0805</td>
<td>2</td>
<td>4 mg</td>
<td>8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39K</td>
<td>R0402</td>
<td>1</td>
<td>0.8 mg</td>
<td>0.8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11K</td>
<td>R0402</td>
<td>1</td>
<td>0.8 mg</td>
<td>0.8 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>270R_TK100_1%</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component type</td>
<td>Average mass per unit</td>
<td>Device code</td>
<td>EIA package code.</td>
<td>Number of SMDs</td>
<td>Specific mass per unit</td>
<td>Total mass</td>
<td>Mass reference</td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------</td>
<td>-------------</td>
<td>-------------------</td>
<td>----------------</td>
<td>------------------------</td>
<td>------------</td>
<td>----------------</td>
</tr>
<tr>
<td><strong>Resistor, SMD type</strong></td>
<td>10 mg</td>
<td>120R_TK100_1%</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td><strong>Panasonic (2008)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4K7_TK100_1%</td>
<td>R0603</td>
<td>1</td>
<td>2 mg</td>
<td>2 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>OR_TK100_1%</td>
<td>R0402</td>
<td>4</td>
<td>0.8 mg</td>
<td>3.2 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4K7_TK100_0.1%</td>
<td>R0402</td>
<td>2</td>
<td>0.8 mg</td>
<td>1.6 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SK5_TK100_0.1%</td>
<td>R0402</td>
<td>2</td>
<td>0.8 mg</td>
<td>1.6 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2K2_TK100_1%</td>
<td>R0402</td>
<td>7</td>
<td>0.8 mg</td>
<td>5.6 mg</td>
<td></td>
</tr>
<tr>
<td><strong>Transistor, SMD type</strong></td>
<td>593 mg</td>
<td>BDP949</td>
<td>SOT223</td>
<td>1</td>
<td>106 mg</td>
<td>106 mg</td>
<td><strong>Infineon (2013e)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPD90P03P4L-04</td>
<td>TO252-3</td>
<td>1</td>
<td>371 mg</td>
<td>371 mg</td>
<td><strong>Infineon (2013j)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BCR183S</td>
<td>SOT363</td>
<td>1</td>
<td>6 mg</td>
<td>6 mg</td>
<td><strong>Infineon (2013d)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BCR1355</td>
<td>SOT363</td>
<td>1</td>
<td>6 mg</td>
<td>6 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BC847PN</td>
<td>SOT363</td>
<td>2</td>
<td>6 mg</td>
<td>12 mg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BSZ15DC02KD</td>
<td>TSDSON8</td>
<td>1</td>
<td>38 mg</td>
<td>38 mg</td>
<td><strong>Infineon (2013f)</strong></td>
</tr>
</tbody>
</table>
Appendix C: Qualitative uncertainty assessment

A qualitative data uncertainty assessment was conducted for the individual flows on the unit process level of the model, based on the Ecoinvent pedigree matrix approach as presented in the overview and methodology report for Ecoinvent version 3 (Weidema et al., 2013). Thus, uncertainty estimations are given for individual data points of each unit process and presented in the table on the following pages. The data points refer to the design and production data presented in the tables of chapters 4 and 5 of this report, but conforming to the format used in the model file where all flows are included and correctly linked. Unlike the model file, the tables of Chapter 5 do not fully report all input flows specified by the design data of Chapter 4 or internal flows between processes. The model file also presents the resulting geometric standard deviations, for the unit process data points, but not for aggregated results.

Lognormal uncertainty distributions were assumed for all flows in line with the “simplified standard procedure” (Weidema et al., 2013). A lognormal distribution is defined by two parameters: the geometric mean (μ) and the geometric standard deviation (GSD). The geometric mean equals the deterministic value of each flow (i.e. the determined amount), whereas the GSD captures the information on the uncertainty (Muller et al., 2014). Basic uncertainty factors (marked with note A in the column heading, see table below) were taken from Table 10.3 of Weidema et al. (2013) and additional quality uncertainty factors (marked with B in the column heading) were generated by evaluating all data according to the pedigree matrix (Table 10.4) and extract corresponding tabulated factors (Table 10.5). All factors were then summarized to form an estimated log-transformed variance σ² of each underlying normal distribution (to the lognormal distributions), in accordance Weidema et al. (2013). The geometric standard deviation each lognormal distribution was calculated using the following definition:

\[ GSD = e^{\sigma} = e^{\sqrt{\sigma^2}} \]

As indicated in Figure 2 of this report, some material flows goes through activities within the extended system boundaries and further into the regular system boundaries as parts. Such flows passing through the extended system have not been assessed for uncertainty to avoid double counting when these flows enter the regular system, unless the activity in the extended system aggregates multiple flows which then passes the regular system boundary or if input flows are required to compensate for losses created by activities in the extended system (for example losses in brass turning). Another exception are extended system material input flows which, after having passed through the extended system, continue directly into regular system process is governed by another property (e.g. by surface area) compared to the activities of the extended system (e.g. by mass). In summary, as a general rule, flows have been assessed at the point in the system where they have been measured or estimated.

A key feature of the LCI model is that is allows the same real-world “unit process” to be modeled taking more than one reference parameter into account. This means that unit processes in the model in some instances are split up into subsections where there are internal flows within the unit process (as a mathematical construction only – in the real world multiple parameters govern the manufacturing process simultaneously). These flows, marked with “within unit process” have not been accesses for uncertainty since they are only a mathematical consequence of the modeling, and have not been measured or estimated.

Furthermore, there are also several cases of internal flows between unit processes marked as “unaltered subpart input” or “unaltered sub-component input”. Similar to the flows passing through the extended system these flows have not been for assessed for uncertainty to avoid multiple assessment for the same data. The precondition is that the flow represents a subpart or subcomponent which remains identical and computationally unaltered within that unit process, although merged with other flows into a more complete part. For example, when the power module baseplate has been electroplated and goes though cleaning it remains unaltered despite that it continues through a new process step.

In order to account for error propagation throughout cumulative results, inventory data for the desired power and torque requirements has to be implemented on the unit process level and calculated in a Monte Carlo simulation tool, by the user. This was not possible to include in the model file as the size of many flows change when the inverter unit size is scaled depending on the input parameters.

Overall, this qualitative assessment of data uncertainty was added to the LCI model to assist users who wish to include uncertainty evaluation based on the Ecoinvent pedigree matrix approach, as a follow-up to the recommendations for how to link all data to Ecoinvent version 3. However, it was never a main goal to build a full pedigree matrix based uncertainty assessment into the aggregated inventory list of the model file.
<table>
<thead>
<tr>
<th>Unit process</th>
<th>Flow name</th>
<th>Report table no.</th>
<th>Basic factor</th>
<th>Reliability</th>
<th>Competence</th>
<th>Temporal correlation</th>
<th>Geographical correlation</th>
<th>Further technical correlation</th>
<th>Log-transformed total variance</th>
<th>—</th>
<th>Geometric standard deviation (GSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabrication of 1 cm² of IGBT chips (for the power module)</td>
<td>Silicon wafer, for power module IGBT chips</td>
<td>-</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td>Electricity for dicing wafer into chips</td>
<td>-</td>
<td>Not assessed for uncertainty since negligible</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Board components and panel input for the driver board, per piece</td>
<td>Unmounted printed circuit board panel</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
</tr>
<tr>
<td>Capacitor, small electrolyte</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitor, surface mounted device type</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitor, tantalum</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connector, clamp type</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode, LED</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode, surface mounted device type</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated circuit, logic type</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductor, chip type</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistor, surface mounted device type</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transistor, surface mounted device type</td>
<td>4</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Board components and panel input for the driver board, per piece</td>
<td>Unmounted printed circuit board panel</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
</tr>
<tr>
<td>Capacitor, small electrolyte</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitor, surface mounted device type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connector, clamp type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connector, switch</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode, LED</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode, surface mounted device type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated circuit, logic type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated circuit, memory type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductor, chip type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductor, multilayer chip type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductor, ring core choke type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistor, surface mounted device type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transistor, surface mounted device type</td>
<td>5</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Printed circuit board assembly per 1 m² of board area (except external connector) (continued on the next page)</td>
<td>Driver board, unassembled</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logic board, unassembled</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning liquid, alkoxypropanol</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning liquid, amino alcohol</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning liquid, deionized water</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solder paste, lead-free</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conformal coating, isoparaffin</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unit process</td>
<td>Flow name</td>
<td>Report table no.</td>
<td>Basic factor</td>
<td>Reliability</td>
<td>Competence</td>
<td>Temporal correlation</td>
<td>Geographical correlation</td>
<td>Further technical correlation</td>
<td>Log-transformed total variance</td>
<td>Sum of all factors (or)</td>
<td>Geometric standard deviation (GSD)</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td>---------------------------------------</td>
<td>------------------</td>
<td>--------------</td>
<td>-------------</td>
<td>-------------</td>
<td>----------------------</td>
<td>--------------------------</td>
<td>------------------------------</td>
<td>---------------------</td>
<td>-----------------------------</td>
<td></td>
</tr>
<tr>
<td><strong>Printed circuit board assembly per 1 m² of board area</strong></td>
<td>Conformal coating, polyaldehyde</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>16</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conformal coating, polycarbamate</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>16</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conformal coating, thinner</td>
<td>15</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>16</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ethanol</td>
<td>16</td>
<td>0.12</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.124125</td>
<td>1.4169</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VOC</td>
<td>16</td>
<td>0.04</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.041425</td>
<td>1.2257</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disposed cleaning liquid, conc. share</td>
<td>16</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Filter waste</td>
<td>16</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solder paste waste</td>
<td>16</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Capacitor materials, per 1 kg</strong></td>
<td>Aluminum</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brass</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Copper</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polycarbonate</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyethylene terephthalate (PET)</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polypropylene</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyurethane resin, C₁₅H₁₀N₂O₂</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polyurethane resin, polyol</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zinc</td>
<td>3/13</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cleaning of 1 m² metal surface before electroplating</strong></td>
<td>Copper bus bars, contacts and plates</td>
<td>-</td>
<td></td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DCB, patterned (not plated)</td>
<td>-</td>
<td></td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brass cable glands</td>
<td>-</td>
<td></td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel terminals, screws and washers</td>
<td>-</td>
<td></td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>17</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Caustic soda</td>
<td>17</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sulfuric acid</td>
<td>17</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>17</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wastewater</td>
<td>18</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electroplating nickel on copper and brass parts, per 1 kg of nickel, and per 1 m² of plated area</strong></td>
<td>Nickel</td>
<td>21</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>21</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nickel (to air)</td>
<td>22</td>
<td>0.65</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.655225</td>
<td>2.2467</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge, dry content</td>
<td>22</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cleaned bus bars, contacts, plates and foils</td>
<td>-</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DCB, patterned, cleaned for plating</td>
<td>-</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cleaned cable glands</td>
<td>-</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>21</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nickel, in sulfamate (to water)</td>
<td>22</td>
<td>0.65</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.655225</td>
<td>2.2467</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wastewater</td>
<td>22</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Internal reference</td>
<td>Uncertainty assessment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unit process</strong></td>
<td><strong>Flow name</strong></td>
<td><strong>Report table no.</strong></td>
<td><strong>Basic factor</strong></td>
<td><strong>Reliability</strong></td>
<td><strong>Completeness</strong></td>
<td><strong>Temporal correlation</strong></td>
<td><strong>Geographical correlation</strong></td>
<td><strong>Further technical correlation</strong></td>
<td><strong>Log-transformed total variance sum of all factors (G2)</strong></td>
<td><strong>Geometric standard deviation (GSD)</strong></td>
<td></td>
</tr>
<tr>
<td>Cleaning (activating) of 1 m² of nickel surface before gold electroplating</td>
<td>Nickel plated contacts (auxiliary terminals)</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrochloric acid</td>
<td>19</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>19</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wastewater</td>
<td>20</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td>Electroplating gold on nickel plated terminals, per 1 kg of gold, and per 1 m² of plated area</td>
<td>Gold</td>
<td>23</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>23</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cyanide (to air)</td>
<td>24</td>
<td>0.12</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.132625</td>
<td>1.4393</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge, dry content</td>
<td>24</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nickel plated contacts, cleaned</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>23</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cyanide (to water)</td>
<td>24</td>
<td>0.3</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.312625</td>
<td>1.7491</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wastewater</td>
<td>24</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td>Electro-galvanizing (zinc plating) of steel parts, per 1 kg of zinc and per 1 m² of plated area</td>
<td>Zinc</td>
<td>25</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>25</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sludge, dry content</td>
<td>26</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cleaned terminals, screws and washers</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>25</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Zinc (to air)</td>
<td>26</td>
<td>0.65</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.662625</td>
<td>2.2570</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wastewater</td>
<td>26</td>
<td>0.0006</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.013225</td>
<td>1.1219</td>
<td></td>
</tr>
<tr>
<td>Copper to be plated, per 1 kg</td>
<td>Copper, slab, for sheet rolling</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Brass to be plated, per 1 kg</td>
<td>Brass, in glands</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Steel to be galvanized, per 1 kg</td>
<td>Low-alloy carbon steel, ingot</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Molding mixture for the power module frame and lid, per 1 kg</td>
<td>Polyphenylene sulfide, powder</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diantimony trioxide</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glass fiber</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Die casting of aluminum, per 1 kg of castings</td>
<td>Aluminum</td>
<td>27</td>
<td>0.0006</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.000625</td>
<td>1.0253</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat, from natural gas</td>
<td>27</td>
<td>0.0006</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.000625</td>
<td>1.0253</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>27</td>
<td>0.0006</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.000625</td>
<td>1.0253</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lubricating oil</td>
<td>27</td>
<td>0.0006</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>0.0107</td>
<td>1.1090</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum (to air)</td>
<td>28</td>
<td>0.65</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.650025</td>
<td>2.2395</td>
<td></td>
</tr>
<tr>
<td></td>
<td>VOC</td>
<td>28</td>
<td>0.04</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>0.048025</td>
<td>1.2450</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waste aluminum</td>
<td>28</td>
<td>0.0006</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0.000625</td>
<td>1.0253</td>
<td></td>
</tr>
<tr>
<td>Machining, per 1 kg of casing (continued on the next page)</td>
<td>Die cast casing parts</td>
<td>29</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0.011225</td>
<td>1.1118</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity, trimming</td>
<td>29</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0.009825</td>
<td>1.1042</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cutting fluid, trimming</td>
<td>29</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0.009825</td>
<td>1.1042</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water, trimming</td>
<td>29</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0.009825</td>
<td>1.1042</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum scrap</td>
<td>30</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0.009825</td>
<td>1.1042</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waste oil, diluted, trimming</td>
<td>30</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>0.009825</td>
<td>1.1042</td>
<td></td>
</tr>
</tbody>
</table>
### Unit process

<table>
<thead>
<tr>
<th>Flow name</th>
<th>Report table no.</th>
<th>Internal reference</th>
<th>Uncertainty assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining, per 1 kg of casing (continued from the previous page)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity, other machining</td>
<td>29</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Electricity, cleaning</td>
<td>29</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Cutting fluid, other machining</td>
<td>29</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Water, other machining</td>
<td>29</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Waste oil, diluted, other machining</td>
<td>30</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Spray painting (liquid cooled heatsink), per 100 g of dried varnish on the casing surface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid varnish, solid share</td>
<td>31</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Liquid varnish, solvent share</td>
<td>31</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Electricity</td>
<td>31</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>VOC</td>
<td>32</td>
<td>0.04</td>
<td>2</td>
</tr>
<tr>
<td>Anodizing 1 m² of aluminum surface area, including masking tape in amounts adopted for the specific casing design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PET foil, masking tape</td>
<td>33</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Electricity</td>
<td>33</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Caustic soda</td>
<td>33</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Nitric acid</td>
<td>33</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Sodium sulfate</td>
<td>33</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Silicone adhesive, masking tape</td>
<td>33</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Water</td>
<td>33</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Wastewater</td>
<td>34</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Masking tape waste</td>
<td>34</td>
<td>0.0006</td>
<td>3</td>
</tr>
<tr>
<td>Fabrication of a 500 µm thick alumina substrate, per 1 m²</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>35</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Electricity</td>
<td>35</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Ammonium polyacrylate</td>
<td>35</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Glycerin</td>
<td>35</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Polyvinyl alcohol</td>
<td>35</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Pure water</td>
<td>35</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Ammonia</td>
<td>36</td>
<td>0.04</td>
<td>2</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>36</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>36</td>
<td>0.65</td>
<td>2</td>
</tr>
<tr>
<td>VOC</td>
<td>36</td>
<td>0.04</td>
<td>2</td>
</tr>
<tr>
<td>Slurry waste</td>
<td>36</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Direct copper bonding of foils and substrate, including cleaning, per 1 m² of DCB before etching (continued on the next page)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alumina substrate</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Copper foils (500 µm thick)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Electricity, cleaning</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Electricity, furnace</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Electricity, ventilation</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
</tr>
<tr>
<td>Acetone</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
</tr>
</tbody>
</table>
Continued from previous page

<table>
<thead>
<tr>
<th>Unit process</th>
<th>Flow name</th>
<th>Report table no.</th>
<th>Basic factor</th>
<th>Reliability</th>
<th>Competence</th>
<th>Temporal correlation</th>
<th>Geographical correlation</th>
<th>Further technical correlation</th>
<th>Log-transformed total variance – sum of all factors (or²)</th>
<th>Geometric standard deviation (GSD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct copper bonding of foils and substrate, including cleaning, per 1 m² of DCB before etching (continued from the previous page)</td>
<td>Deionized water</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td></td>
<td>Hydrochloric acid</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td></td>
<td>Isopropanol</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td></td>
<td>Nitrogen</td>
<td>37</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td></td>
<td>Waste solvents, conc. share of dilution</td>
<td>38</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td>Photolithographic regenerative etching of the upper copper foil of the DCB, per 1 kg of copper to be removed and per 1 m² of DCB substrate area</td>
<td>Copper in upper foil to be removed</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.002625</td>
<td>1.0526</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>39</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Chlorine gas</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Hydrochloric acid</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Cupric chloride</td>
<td>40</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>DCB, before etching</td>
<td>-</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Acetone</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Potassium carbonate</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Isopropanol</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Photoresist</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Potassium hydroxide</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>Water</td>
<td>39</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td></td>
<td>VOC</td>
<td>40</td>
<td>0.04</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.090625</td>
<td>1.3513</td>
</tr>
<tr>
<td></td>
<td>Waste solvents, conc. share of dilution</td>
<td>40</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>0.051225</td>
<td>1.2540</td>
</tr>
<tr>
<td>Pre-solder cleaning, including vacuum baking, per 1 m² of DCB or baseplate</td>
<td>DCB, patterned, nickel plated</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Baseplate, nickel plated</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity, furnace</td>
<td>47</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Electricity, ventilation</td>
<td>47</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Deionized water</td>
<td>47</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td></td>
<td>Isopropanol</td>
<td>47</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td></td>
<td>Waste solvents, conc. share of dilution</td>
<td>48</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.0444</td>
<td>1.2346</td>
</tr>
<tr>
<td>Soldering of the power module with vacuum VPS diffusion soldering for chip attachment and reflow system soldering to connect DCB and baseplate, including stencil printing and cleaning of stencils, per 1 m² of DCB and/or per 1 m² of baseplate... (continued on the next page)</td>
<td>DCB substrate, cleaned and baked</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Baseplate, cleaned and baked</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>41</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Cleaning liquid, alkoxynpropanol</td>
<td>41</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Cleaning liquid, amino alcohol</td>
<td>41</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Cleaning liquid, deionized water</td>
<td>41</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Disposed cleaning liquid, conc. share</td>
<td>42</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Solder paste</td>
<td>43</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Ethanol</td>
<td>44</td>
<td>0.12</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.121425</td>
<td>1.4169</td>
</tr>
<tr>
<td></td>
<td>VOC</td>
<td>44</td>
<td>0.04</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.041425</td>
<td>1.2257</td>
</tr>
<tr>
<td>Unit process</td>
<td>Flow name</td>
<td>Report table no.</td>
<td>Basic factor</td>
<td>Reliability</td>
<td>Completeness</td>
<td>Temporal correlation</td>
<td>Geographical correlation</td>
<td>Further technical correlation</td>
<td>Log transformed total variance</td>
<td>Geometric standard deviation (GSD)</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td>------------------</td>
<td>--------------</td>
<td>-------------</td>
<td>--------------</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>... (area on one side – not total surface area), and per 1 kg of lead-free solder in the power module (continued from the previous page)</td>
<td>Filter waste</td>
<td>44</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.002025</td>
<td>1.0460</td>
</tr>
<tr>
<td>Solder paste waste</td>
<td>-</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td>Diced IGBT chips</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
</tr>
<tr>
<td>Electricity (chip attachment)</td>
<td>45</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>0.04025</td>
<td>1.2275</td>
<td></td>
</tr>
<tr>
<td>Electricity (system soldering)</td>
<td>46</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.010025</td>
<td>1.1053</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>46</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.010025</td>
<td>1.1053</td>
<td></td>
</tr>
<tr>
<td>Post-solder solvent cleaning, per 1 m² of baseplate (area on one side – not total surface area)</td>
<td>Baseplate module w/o frame</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetone</td>
<td>49</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.04444</td>
<td>1.2346</td>
<td></td>
</tr>
<tr>
<td>Isopropanol</td>
<td>-</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.04444</td>
<td>1.2346</td>
<td></td>
</tr>
<tr>
<td>Waste solvents, conc. share of dilution</td>
<td>49</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>0.04444</td>
<td>1.2346</td>
<td></td>
</tr>
<tr>
<td>Attachment of plastic frame, per 1 piece</td>
<td>Baseplate module w/o frame, cleaned</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galvanized terminals, screws and washers</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frame with bonded terminals</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicone adhesive</td>
<td>48</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
</tr>
<tr>
<td>Ultrasonic bonding of wires and terminals, per 1 cm² of IGBT chip area</td>
<td>Baseplate module with frame</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper wire</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity for ultrasonic welding</td>
<td>-</td>
<td>0.0006</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.005425</td>
<td>1.0764</td>
<td></td>
</tr>
<tr>
<td>Potting and curing with UV lights, per kg of potting gel layer and per 1 piece</td>
<td>Silicone potting gel</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity for dispensing gel</td>
<td>-</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.004025</td>
<td>1.0655</td>
<td></td>
</tr>
<tr>
<td>Power module, open, wire bonded</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity UV curing</td>
<td>-</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0.005825</td>
<td>1.0793</td>
<td></td>
</tr>
<tr>
<td>Attachment of plastic lid, per 1 piece</td>
<td>Power module, open, potted</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lid</td>
<td>-</td>
<td>Unaltered sub-component input</td>
<td>1.0000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicone adhesive</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
<td></td>
</tr>
<tr>
<td>Selective soldering for mounting the external connector to the logic board, per 1 m² of PCB area employed for mounting the external connector</td>
<td>Logic board, assembled, w/o connector</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td>External connector for logic board</td>
<td>51</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.004025</td>
<td>1.0655</td>
<td></td>
</tr>
<tr>
<td>Solder bar, lead free</td>
<td>51</td>
<td>0.0006</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.004025</td>
<td>1.0655</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>51</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td>Flux, aqueous, dicarboxylic acid share</td>
<td>51</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td>Flux, aqueous, deionized water share</td>
<td>51</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td>51</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td>Solder waste</td>
<td>52</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
<td></td>
</tr>
<tr>
<td>Unit process</td>
<td>Flow name</td>
<td>Report table no.</td>
<td>Basic factor$^a$</td>
<td>Reliability$^a$</td>
<td>Completeness$^a$</td>
<td>Temporal correlation$^a$</td>
<td>Geographical correlation$^a$</td>
<td>Further technical correlation$^a$</td>
<td>Log-transformed total variance – sum of all factors (σ$^2$)</td>
<td>Geometric standard deviation (GSD)</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------</td>
<td>-----------------</td>
<td>-----------------</td>
<td>---------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td><strong>Final assembly of inverter unit using hand held tools, per 1 kg of IGBT inverter unit (complete)</strong></td>
<td>Driver board, assembled</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Logic board, assembled, with connector</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>DC link capacitor</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>IGBT power module, complete</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Galvanized screws and washers</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Plated cable glands</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Lamellar inserts (for glands)</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>O-rings and gland seals (for glands)</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Nylon distance spacers</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Bus bar, laminated</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>Machined casing, surface treated</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>TIM - aluminium oxide</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>TIM - zinc oxide</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td></td>
<td>TIM - silicone oil</td>
<td>-</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0.001425</td>
<td>1.0385</td>
</tr>
<tr>
<td><strong>Technical building services, per 1 m² of PCB (for building services in PCB assembly), per 1 m² of DCB (for building services in the DCB and power module assembly), and per 1 piece (for building services in casing manufacturing, and for final inverter unit assembly)</strong></td>
<td>Electricity for compressed air (PCBs)</td>
<td>53</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
</tr>
<tr>
<td></td>
<td>Electricity for vent. and cooling, (PCBs)</td>
<td>53</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
</tr>
<tr>
<td></td>
<td>General electricity and machinery (PCBs)</td>
<td>53</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
</tr>
<tr>
<td></td>
<td>Electricity for compressed air (DCB &amp; pm)</td>
<td>55</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Electricity for vent. and cooling (DCB &amp; pm)</td>
<td>55</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>General electr. and machinery (DCB &amp; pm)</td>
<td>55</td>
<td>0.0006</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.010025</td>
<td>1.1053</td>
</tr>
<tr>
<td></td>
<td>Electricity for compressed air (casing)</td>
<td>56</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.009425</td>
<td>1.1020</td>
</tr>
<tr>
<td></td>
<td>Electricity for heating (casing)</td>
<td>56</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.009425</td>
<td>1.1020</td>
</tr>
<tr>
<td></td>
<td>Electricity for ventilation (casing)</td>
<td>56</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.009425</td>
<td>1.1020</td>
</tr>
<tr>
<td></td>
<td>General electricity and machinery (casing)</td>
<td>56</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.009425</td>
<td>1.1020</td>
</tr>
<tr>
<td></td>
<td>Electricity for compressed air (final ass.)</td>
<td>54</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
</tr>
<tr>
<td></td>
<td>Electricity for heating (final ass.)</td>
<td>54</td>
<td>0.0006</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0.002025</td>
<td>1.0460</td>
</tr>
</tbody>
</table>