Quantifying the Value of Power Electronics in Sustainable Electrical Energy Systems

Jelena Popović-Gerber, *Member, IEEE*, Jan Abraham Ferreira, *Fellow, IEEE*, and Jacobus Daniel van Wyk, *Associate Member, IEEE*

***Abstract*—Power electronics enables the efficient generation, use, and distribution of electrical energy because it substantially improves energy conversion efficiency. In order to realize the large electrical energy savings potential enabled by power electronics suitable technological solutions at acceptable cost levels are needed. Moreover, public policy and public acceptance must play an increasingly important role. An effective way to quantify the value of power electronics is needed and it must be presented in such a way that it is understood and appreciated by policymakers. In this paper, energy payback time is shown to be a powerful tool for weighing the value of energy savings achieved by using power electronics versus the energy needed to manufacture the systems. A life cycle analysis of two power electronic converters and their parts is performed. The benefits of energy savings versus energy invested in manufacturing and end-of-life management of power converters is analyzed. It is shown that power electronics systems have considerably shorter energy payback time compared to other technologies.**

***Index Terms*—Energy efficiency, life cycle analysis, power electronics.**

I. Power Electronics in a Sustainable Electrical Energy System

THE ever increasing demand for energy, the dwindling of fossil fuel reserves and the need for carbon footprint reduction have resulted in a global awareness of the importance of energy savings and energy efficiency. This topic is taking high priority in today's society, leading to many new governmental policies and measures, industrial awareness and research being conducted all over the world. Combating the energy and climate problems requires a complex, multidisciplinary approach that necessitates technological solutions such as sustainable energy sources and more efficient energy use alongside political measures and a commitment from the general public [1]–[5].

After the first phase of energy efficiency awareness, a phase where energy efficiency and sustainability are becoming more sophisticated has begun [6], [7]. Efficiency of electrical energy conversion is replaced by overall system energy efficiency. The energy consumed and CO_2 emissions produced over the full life cycle of energy processing systems are becoming important [8], [9]. The authors believe that the challenge is to evolve technological systems into a form that is comparable to biological systems that have been self-sustainable since the evolution of life on earth. Fig. 1 shows an analogy between a sustainable biological system and a sustainable technological system based on electricity as an energy carrier. The sustainable biological system provides nutrients both for the day/night cycles of biological loads but also for the cradle and grave part of the total life cycle. In the same way, the technological nutrients have to supply the energy required for manufacturing and end-of-life management of electrical loads and the energy for their operational cycles. An energy balance has to be achieved for the full life cycle of the electrical energy system.

The demand for electrical energy is continuously growing and will continue to do so at a rate twice as fast as overall energy consumption [10], [11]. Today 20% of all final energy consumption in the EU is electrical energy, but this is predicted to grow significantly over the next few decades [12]. Power electronics is the enabling technology to efficiently condition electrical energy after generation and during distribution and use, and is a key constituent of sustainable electrical energy systems [13]–[16]. According to [17], widespread use of power electronics in buildings, lighting, power supplies, and motor drives can result in 25% reduction of the total electrical energy consumption in the European Union.

Awareness of power electronics as an important enabling technology for more efficient electrical energy usage has increased as can be seen in national energy policies and technology programs [18], [19], but there is still a long way to go before reaching full acceptance and exploitation of its potential. Furthermore, due to the enormous attention sustainable energy is receiving, new players are joining the game, changing the dynamics of technology development. It is not only about suitable technological solutions at acceptable cost, but policy and public acceptance are playing an increasingly important role [20]. Furthermore, improvements are sought on a high system level where the perceived importance of power electronics may not be evident. Consequently, improved and more effective ways of showing the importance and value of power electronics are needed. It is necessary to convincingly quantify the energy savings

Manuscript received January 1, 2011; revised July 3, 2011; accepted August 8, 2011. Date of current version December 6, 2011. This work was supported in part by the European Centre for Power Electronics (ECPE). This paper is a revised version of the paper presented at the IEEE Energy Conversion Congress and Exposition (ECCE), Atlanta, Georgia, September 12–16, 2010. Recommended for publication by Associate Editor (Letters AE) J. Biela.

J. Popovic-Gerber is with the Delft University of Technology, Delft, The Netherlands, and with the European Centre for Power Electronics, Nuremberg, Germany (e-mail: j.popovic@tudelft.nl).

J. A. Ferreira is with Delft University of Technology, Delft, The Netherlands (e-mail: j.a.ferreira@tudelft.nl).

J. D. van Wyk is with the Group on Electronic Energy Processing, Department of Electrical and Electronic Engineering Science, University of Johannesburg, Kingsway Campus, Auckland Park Johannesburg, South Africa (e-mail: daan@ieee.org).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPEL.2011.2166088

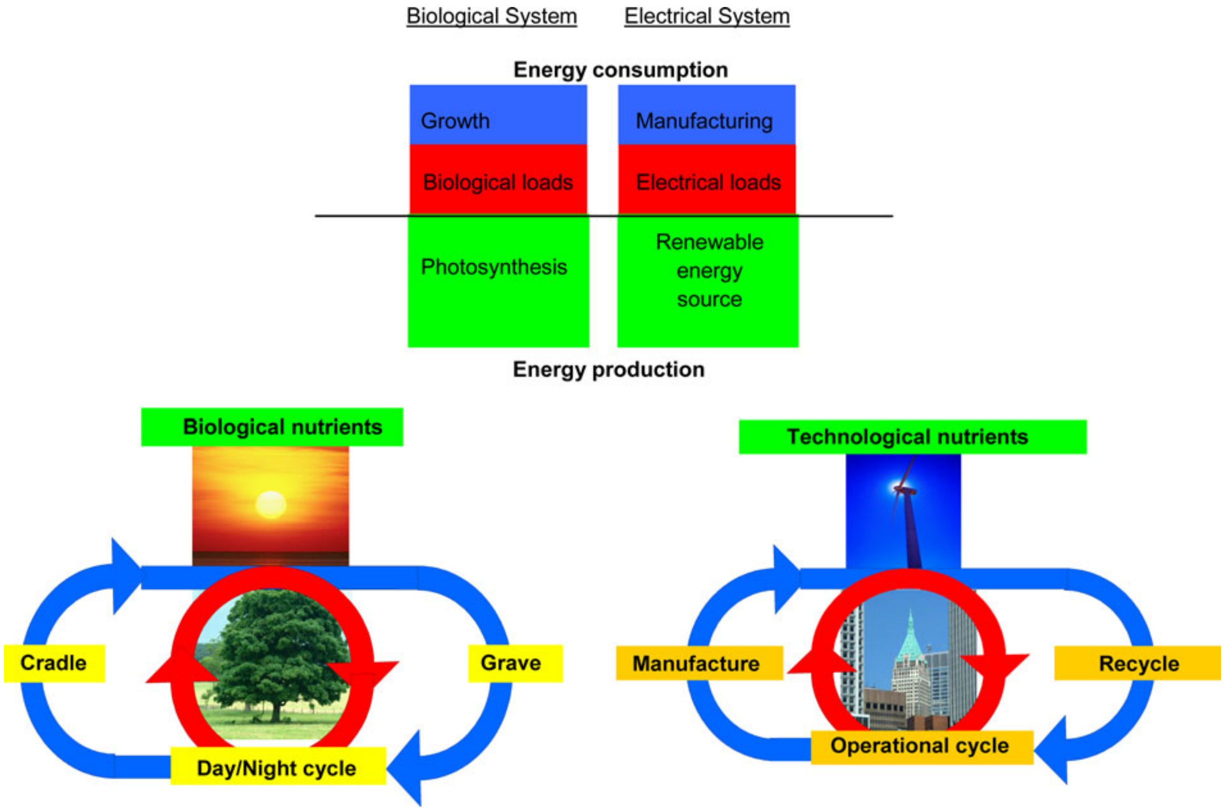


Fig. 1. Mimicking nature with electrical technology.

potential not only in terms of kWh but in a way that can be understood by policy makers and that can capture the imagination of the general public. This includes weighing the energy saving benefits against the associated investments. In this paper, some possibilities of quantifying the added value of using more power electronics will be explored, as well as how power electronics systems can contribute to achieving fully sustainable energy systems.

In Section II, energy payback time as a widely used figure-of-merit for renewable energy sources is revised in the light of sustainable energy systems and the concept of sustainable energy balance is introduced. The contribution of power electronics in shortening the time to achieve sustainable energy balance is discussed and the concept of power electronics energy payback time is introduced. In Section III, a life cycle analysis of two power electronic converters is presented and the relationships between different energy components in the life cycle of the converters are discussed. In Section IV, the concepts of power electronics energy payback time and sustainable energy balance reduction by means of power electronics are illustrated by means of a few case studies.

II. Quantifying the Contribution of Power Electronics to Sustainable Energy Systems

A. Energy Payback Time of Renewable Energy Sources

Renewable energy sources are receiving considerable political and public attention worldwide. Research topics closely related to renewable energy sources are widely present in national, EU, and worldwide research programs. In Europe, technology platforms as frameworks for stakeholders to define research and development priorities on wind energy, photovoltaic systems and biofuels have been put in place [21].

A powerful and transparent figure-of-merit of renewable energy sources is energy payback time (EPBT) defined as the time required for an energy producing system or device to generate as much energy as was required for its manufacturing [22]–[25]. Energy payback time is a well-accepted concept because it is analogous to the well-understood principle in the business world of "economic payback time" defined as the period of time required for the return on an investment to "repay" the sum of the original investment which in the case of renewable energy systems would translate into the time required to generate as much economic value in energy as was spent to purchase the system.

Fig. 2 illustrates the basic principle of energy payback time. The time it takes to recover the embodied energy of a renewable energy system (energy required to manufacture, install, and commission and recycle the system) ($E_{\mathrm{emb\_res}}$) through the energy the system delivers (E_{del}) is the energy payback time (EPBT) of a renewable energy system:

$$\mathrm{EPBT} = \frac{E_{\mathrm{emb\_RES}}}{E_{\mathrm{del}}/\mathrm{year}}. \qquad (1)$$

For example, the energy payback time of a wind turbine is currently around 6–8 months [26]–[29] and of photovoltaic systems 1–3 years [30], [31], depending on the technology.

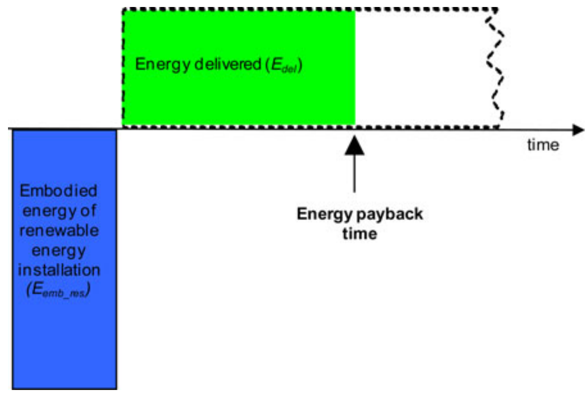


Fig. 2. Energy payback time of renewable energy sources.

B. Energy Balance of Sustainable Energy Systems

In order to quantify the value of energy savings methodologies in a way that can be used to measure our progress on the path to full sustainability, it is necessary to revisit the concept of energy payback time of renewable energy sources. As shown in Fig. 1, the generated energy not only has to recover the embodied energy of the generator, but it also has to supply the manufacturing and daily operational energy of all the electrical loads in the system. As indicated in Fig. 3, the system only becomes truly autonomous from an energy point when the energy requirement of the full system is considered. The point in time when the energy delivered by a renewable energy source (E_{del}) becomes equal to the sum of the embodied energy of the renewable energy source installation ($E_{\mathrm{emb\_RES}}$), the embodied energy of the electrical equipment ($E_{\mathrm{emb\_loads}}$) and the energy consumed by the equipment (E_{loads}) is defined as the sustainable energy balance (SEB):

$$E_{\mathrm{del}} = E_{\mathrm{loads}} + E_{\mathrm{emb\_RES}} + E_{\mathrm{emb\_loads}} \tag{2}$$

$$\mathrm{SEB} = \frac{E_{\mathrm{emb\_RES}} + E_{\mathrm{emb\_loads}}}{(E_{\mathrm{del}} - E_{\mathrm{loads}})/\mathrm{year}}. \tag{3}$$

C. Power Electronics Energy Payback Time

Alongside renewable energy sources, an important component of the complex energy and climate combat plan is energy efficiency and energy savings. It has been widely recognized that the most sustainable energy is energy saved. In the European Commission Action Plan for Energy Efficiency, energy savings or "Negajoules" are recognized as the single most important energy source and a large contributor to energy supply security [32].

Energy savings reduce the portion of the renewable energy that is consumed by the electrical equipment, making more energy available that can be allocated to manufacturing, as well as other electrical loads and their consumption, as is shown in Fig. 4. Since the embodied energy can be recovered in a shorter period, the sustainable energy balance is achieved sooner. If the energy savings is achieved by installing a power electronic converter in the system, its embodied energy has to be added to the energy balance equation. However, this energy is re-couped after a certain time due to energy savings that are achieved. This time interval is defined as the energy payback time of the power electronic converter. The power electronic converter energy payback time (PE EPBT) can then be expressed as:

$$\text{PE EPBT} = \frac{\Delta(E_{\mathrm{emb}})_{\mathrm{system}}}{(\Delta E_{\mathrm{loads}})_{\mathrm{system}}/\mathrm{year}} \tag{4}$$

where

1) $(\Delta E_{\mathrm{emb}})_{\mathrm{system}}$ is the difference in the embodied energy of the conventional system and the modified system. If the only difference is in introducing a power electronic converter and the rest of the system stays the same then $(\Delta E_{\mathrm{emb}})_{\mathrm{system}}$ is equal to the embodied energy of the power electronics converter $E_{\mathrm{emb\_conv}}$.
2) $(\Delta E_{\mathrm{loads}})_{\mathrm{system}}$ is the difference in the operational energy of the conventional system (before the modification) and the modified system. This is the energy saved over the operational time of the system E_{sav} by introducing the modification (a power electronic converter).

$$\text{PE EPBT} = \frac{E_{\mathrm{emb\_conv}}}{E_{\mathrm{sav}}/\mathrm{year}}. \tag{5}$$

As an example, if in the case of photovoltaic systems, a dc/dc converter is introduced for each solar panel thus achieving distributed maximum power point tracking (MPPT) [33], [34], $(\Delta E_{\mathrm{emb}})_{\mathrm{system}}$ would be the embodied energy of the dc/dc converters and $(\Delta E_{\mathrm{loads}})_{\mathrm{system}}$ would represent the increase in energy output of the PV system by optimizing the operating point of each solar panel.

Looking at the total system, by introducing power electronics into sustainable energy systems the energy consumed by the loads is reduced (E'_{loads}) and the sustainable energy balance SEB' is modified to:

$$E_{\mathrm{del}} = E'_{\mathrm{loads}} + E_{\mathrm{emb\_RES}} + E_{\mathrm{emb\_loads}} + E_{\mathrm{emb\_conv}} \tag{6}$$

$$\mathrm{SEB'} = \frac{E_{\mathrm{emb\_RES}} + E_{\mathrm{emb\_loads}} + E_{\mathrm{emb\_conv}}}{(E_{\mathrm{del}} - E'_{\mathrm{loads}})/\mathrm{year}}. \tag{7}$$

Assuming that the reduction in the energy consumption in the system is much larger than the influence of the added embodied energy of the power electronic converter, the sustainable energy balance of the system will be reduced.

III. Life Cycle Analysis of Power Electronic Converters for Motor Drives

As can be seen from (5), in order to calculate the energy payback time of a converter it is necessary to know its embodied energy. To this end, a life cycle analysis of two inverters for variable speed drives, rated at 2.2 kW and 11 kW, was performed. The choice of drive ratings was determined by availability of and information on the hardware.

Life cycle analysis (LCA) is a relatively new technique for assessing the environmental aspects associated with a product

Fig. 3. Sustainable energy balance of an energy system.

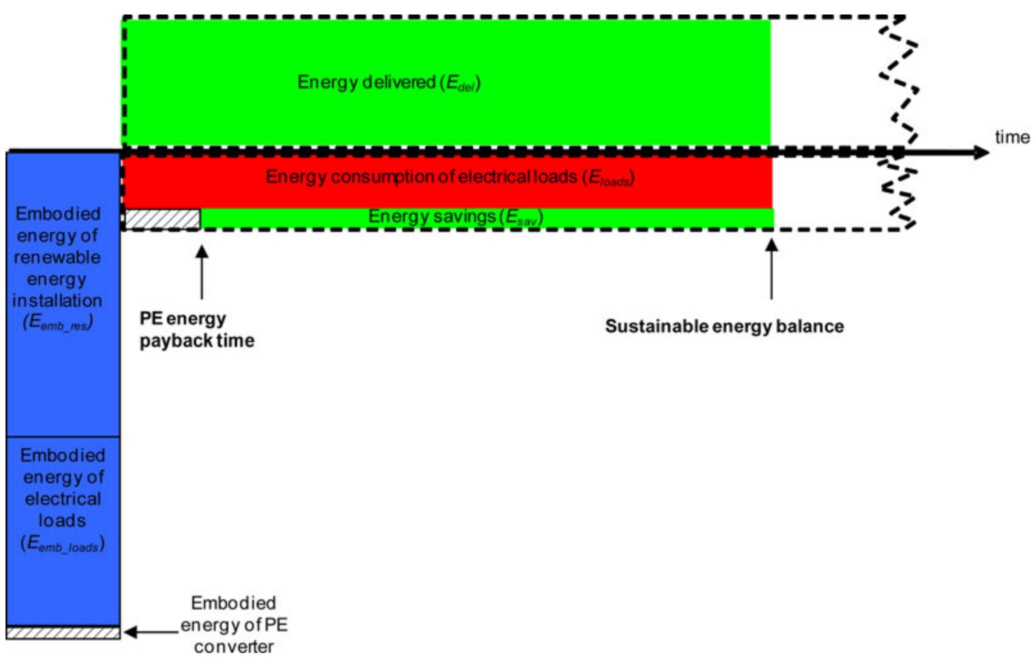


Fig. 4. Saving energy and improving sustainable energy balance with power electronics.

over its life cycle [35]. The result of the assessment is typically a single indicator taking into account one or more environmental issues such as materials depletion, emissions, and energy. There are many methods used to develop such an indicator, some focusing on only one of the three issues, others combining all three [36]. Since we are interested in the energy content of the assemblies, the cumulative energy demand indicator (CED) was used as the life cycle analysis indicator [37] which gives the total (primary) energy use through a life cycle the life cycle of a product or a service. This includes the direct uses as well as the indirect or gray consumption of energy due to the use of, e.g., construction materials or raw materials. The life cycle inventory databases used were EcoInvent, Idemat, ICE, and CES [38]–[41]. The analysis only includes the cradle-to-gate data, so the end-of-life management is not included. Considering that the energy content of the end-of-life management (disposal, recycling) for most of the electronic waste is several orders of magnitude smaller than the cradle-to-gate energy content the presented analysis gives a satisfactory picture of the total life cycle energy content. For example, the eco-costs indicator (single LCA-based indicator based on the concept of "marginal prevention costs" [42]) of the gate-to-cradle part of the life cycle for an assembled surface mount PCB is ∼100 €/kg while the respective value for the waste treatment is 0.017 €/kg [38].

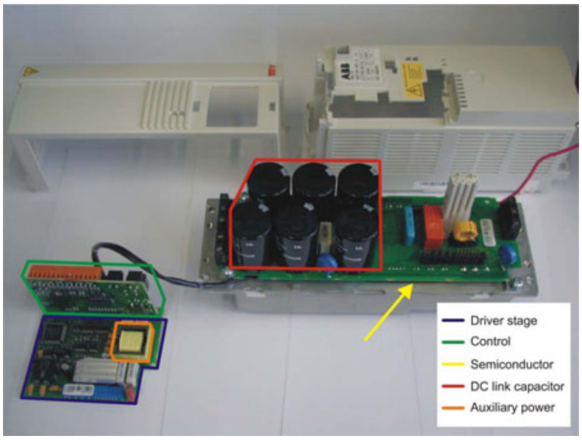


Fig. 5. The 2.2 kW drive assembly.

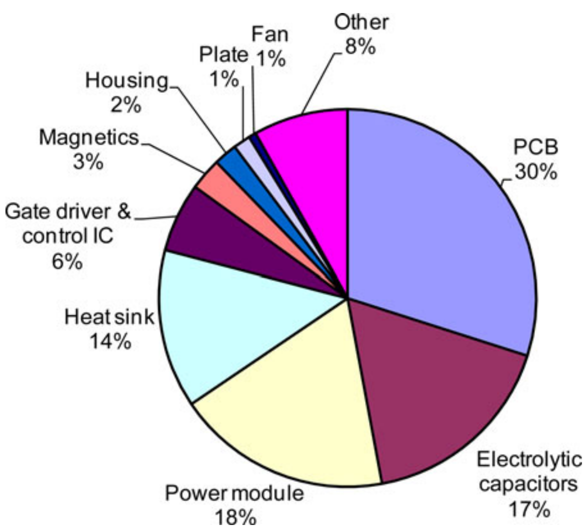


Fig. 6. Cumulative energy demand (CED) breakdown of the 2.2 kW drive.

A. LCA of a 2.2 kW and a 11 kW Inverter for ac Drives

Fig. 5 shows the disassembled 2.2 kW drive. Several distinctive subassemblies can be identified: the housing, the main power board with the heat sink, and the two auxiliary boards including the control board and the auxiliary power supply/gate driver board. The power module is of the dual-in-line-package converter-inverter-brake (DIP-CIBs) type, in which bare power semiconductor dies are assembled on a lead frame and transfer moulded [43], [44]. The dc-link filter on the power board consists of capacitors only (six capacitors are placed on the board, two connected in series, each capacitor has a capacitance of 280 μF). The heatsink of the drive is actively cooled by a fan.

A life-cycle inventory of the converter's assembly parts using the CED indicator was performed using the databases discussed at the beginning of Section III. The total CED value of the assembly is 1207J and Fig. 6 shows the biggest contributors of the total CED value as a percentage of the total value. From these results it can be determined that the PCBs (the CED indicators include the assembly of the components), electrolytic capacitors, power module, and heat sink are the biggest contributors. The control and gate driver integrated circuits, transformer and choke, and the housing contribute to a smaller extent.

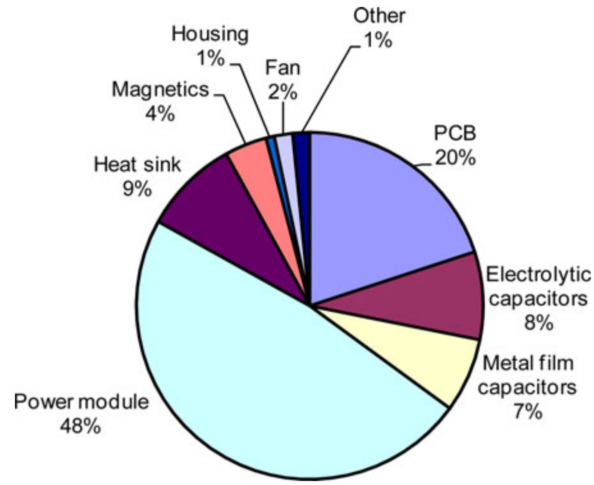


Fig. 7. Cumulative energy demand (CED) breakdown of the 11 kW drive.

The main parts of the 11 kW drive assembly are the power module (type SkiiP 3, which is a spring pressure contact based module with no base plate that integrates power semiconductor switches, heat sink, and gate driver unit with protection and monitoring circuit [45]), three FR4 PCBs (the main power board, the dc link, and filters board and the auxiliary board), eight electrolytic capacitors in the dc link, 6 X2 polypropylene metal film capacitors, the filter choke, and the power supply transformer. The power module is mounted on the aluminium heat sink and the whole converter is encased in a POCAN plastic housing. The internal frame is made of 1-mm-thick galvanized steel plate. The converter is cooled by two fans.

Similar to the analysis of the 2.2 kW drive, a life-cycle inventory of the converter's assembly parts using the CED indicator was performed using the databases discussed at the beginning of Section III. The total CED value of the assembly is 7490J. The CED distribution is shown in Fig. 7. The biggest contributors are the power module (48%), the PCBs (20%), the capacitors (aluminium 8% and metal film 7%), and the heatsink (9%).

B. The Used LCA Data and Its Uncertainties

The data for the CED indicator for both drives are obtained from the aforementioned databases, Ecoinvent and Idemat. Unfortunately but as expected not all parts and processes relevant to the two converters were available in these databases. The following assumptions were made:

1) Since the energy content of power semiconductors was not available, the database value for fabricated IC wafer of the same surface area was taken. A few power semiconductor and module manufacturers were contacted and the joint conclusion was that the power semiconductor market is relatively small and as far as we were able to ascertain, no such data exist for power semiconductors. However, as the Si crystal growth contributes the largest part of the energy consumption in manufacturing, power

TABLE I
LCA RESULTS AND IMPLICATIONS

	CED [MJ]	Embodied energy [kWh]	Cost of embodied energy /total price	Saved energy annually [kWh]	Processed energy annually [kWh]	Dissipated energy annually [kWh]	Embodied energy/ saved energy	Embodied energy/ dissipated energy	Energy payback time [months]
2.2kW	1350,0	129,3	1,6%	3851	6097	182,9	0,34%	7,1%	0,4
11kW	8240,0	801,1	2,4%	19853	32331	969,9	0,40%	8,3%	0,5

semiconductors can be considered to have the same energy consumption. It is realized that power semiconductor die are appreciably thicker than IC die. However, it was assumed that this and the different furnace processes of power semiconductors are compensated by more mask steps etc. in case of the IC. Therefore, using the same numerical value as for ICs should give a fair approximation.

2) Looking at the assembly of a power module, for example, for an assumed 500 A/1200 V-module, the cost of utilities per module (including electricity, gas, water, etc.) according to a power module manufacturer is around 10 to 20 euro cents, which is negligible. Therefore, the production of the raw materials within a module consumes much more energy and resources and is the main contributor to the total energy content. The housing and pressure plate were added to the inventory, the rest of the assembly was omitted.

C. Discussion

Now that the LCA for the two converters has been performed, let us take a closer look at the results. To get a complete picture, the following questions should be answered:

1) How does the embodied energy compare to the energy saved by using a VSD in a motor drive system? This translates into the energy payback time of the VSD.
2) What is the ratio of the embodied energy to the energy dissipated by the converter over its lifetime? This gives an indication of how sensible it is to invest in decreasing the embodied energy by using alternative technologies compared to investing the effort in improving the conversion efficiency of converters.
3) Looking at the biggest contributors to the total embodied energy for the two case studies, what alternative technologies could be used for these parts and would it be feasible to use them? How could the ecoperformance of a component be related to its functional (electrical, thermal, mechanical) performance for different components?

1) Energy Payback Time - Embodied Energy Versus Saved Energy: Table I shows the processed results of the analysis for the two converters. The data for the purchase price, saved and processed energy are obtained from the ABB calculator [46]. The data for the dissipated energy are obtained assuming a 97% efficiency of the converters (typical data-sheet value).

Table I shows the ratio of the cost of the embodied energy to the total purchasing price. For both case studies the calculated total CED values were increased by 10% to take into account the miscellaneous parts that were not included in the analysis. Since this is the primary energy, if one wants to convert it to kWh of electricity, assuming an average thermal plant efficiency of 35%, one gets the energy content in kWh of 128 kWh. If this is converted back into monetary units and compared to the purchase price, the cost of embodied energy is about 2% of the total purchase price for both converters which is less than the 5% estimation used in calculating the energy payback time for different converters in Section III. This will reflect in a shorter energy payback time than estimated, at least for the VSD study, since for different type and application of converters the situation may be different. It can be seen that the energy payback time calculated with the obtained values of embodied energy is in the range of half a month for both cases.

Table I also shows the relative ratio of the embodied energy to total saved energy over the lifetime of the converter. Obviously, this is directly related to the energy payback time value but it also depends on the estimated life time of the converter (here estimated to be ten years). It can be seen that the embodied energy is less than half a percent of the total saved energy.

2) Embodied Energy Versus Dissipated Energy: The total life-cycle energy of the converter, or the energy that converter "uses" over its life time, consists of the embodied energy and the energy dissipated through losses during its operation. Even though, as we have seen in the previous section, the energy payback time of the inverters is already very short, if we look at further reducing the life cycle energy of the converter, it makes sense to look at where the biggest contribution lies. From Table I it can be seen that the embodied energy is less than 10% of the dissipated energy (for the assumed 97% efficiency at all loads which is an overestimation) which means that the main effort in decreasing the total life-cycle energy should be invested in increasing the efficiency of the converter. Of course, this may mean using technologies that are higher in energy content which would increase the embodied energy so this should be kept in mind. For the sake of illustration, assuming that the converter's efficiency is 99% while the embodied energy remains unchanged, the embodied energy would be around 20% of the dissipated energy.

3) Embodied Energy of Various Components: As previously mentioned, once the main contributors to the total embodied energy are identified, it is useful to look into possible alternatives for high energy content components or assembly processes. Unfortunately, the databases utilized in this study do not contain data for an extensive array of electronic components, especially not for newer technologies such as wide band gap semiconductors so it was not possible to conduct an in depth analysis of this kind. One can however, look into certain parts.

Looking at the breakdown of the total embodied energy in the two case studies, it can be ascertained that the heat sink contributes around 10%–15% of the total CED value. Reference [47] compares aluminium and thermally conductive polymer heat sinks in terms of performance (cooling capability) and eco-impact (embodied energy of the heat sink) and shows that the performance/eco-impact ratio for polyphenylene sulphide (PPS) polymer is approximately 4.5, or nearly three times greater than that of the aluminium counterpart with the ratio of 1.6. It should be noted that the embodied energy of aluminium used in this work, 200 MJ/kg, is higher than the worldwide standard (33% recycled) 155 MJ/kg [40], which will make the above ratio just above 2.

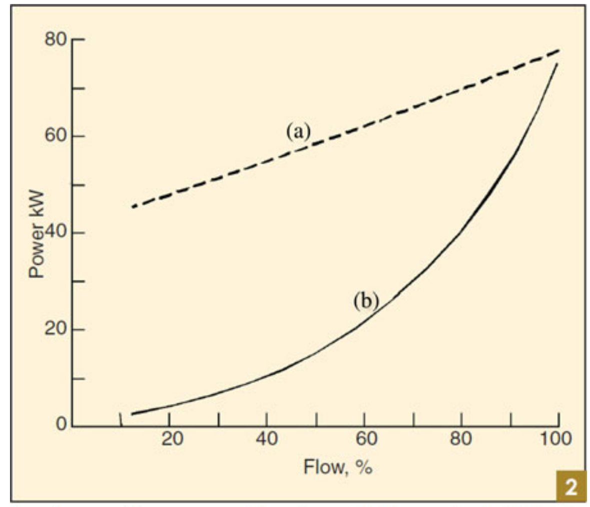
Considering different capacitor technologies, the CED of metal film capacitors is 1122 MJ/kg while the CED of electrolytic capacitors is 945 MJ/kg [39]. The respective energy densities (rated at 400 V) are 605 J/kg for the electrolytic capacitor and 29 J/kg for the metal film capacitor. So, if one looks at the energy density/embodied energy ratio as the performance/eco-impact ratio, the value for the electrolytic capacitor is $6.4 \cdot 10^{-7}$ and for the metal film capacitor is $2.6 \cdot 10^{-8}$ or 25 times smaller.

IV. Case Studies – Energy Payback Time and Sustainable Energy Balance Reduction

In the following examples, a first order estimation of the energy payback time of several systems in which power electronics is used is made. The values of energy saved by introducing power electronics into systems is taken from the literature published by the manufacturers. Concerning embodied energy in Section III, it is shown that for low power VSDs up to 2.5% of the purchase cost is attributed to embodied energy, which can be translated into ~800 MJ/kWh. Literature shows that for PV inverters this value varies between 800–1300 MJ/kW$_\mathrm{p}$ [48]–[50]. Since the case studies involve converters for diverse applications (some more technologically complex than a VSD drive) and power levels, a value of 5% of the purchase cost will be attributed to embodied energy. This value is most likely on the high side and will show the worst-case scenario of power electronics energy payback time. Lastly, a hypothetical sustainable energy system is created to illustrate how the use of power electronics shortens the sustainable energy balance of the system.

A. Power Electronics Energy Payback Time—Case Studies

1) Variable Speed Drive: The energy saving potential of variable speed drives (VSDs) comes from the ability to control the motor speed to match the output with the system needs [51, Fig. 8]. This is enabled by power electronic inverters that supply variable frequency voltage to the motor thus changing its speed. This is particularly beneficial in fluid and motion applications, such as pumps and fans, where the flow or speed vary over time. Looking at the total life cycle of motor driven systems, energy costs during the operation of the drive are often bigger than 90% of the total life cycle costs [52]. For pump driven systems, the life cycle cost breakdown is: energy 80%, purchase 8%, and maintenance 12% [53]. By introducing VSDs in motor driven systems, energy savings of 30-40% on average and up to 60–70% in certain applications can be achieved [53] [54].



Input power for a pump driven by a 100-hp motor. (a) Direct drive and output throttle valve. (b) Drive via 100-kVA ASD.

Fig. 8. Energy savings for variable speed driven pumps [51].

A 50 kW variable speed drive is taken as a case study. The values for the drive price used to estimate the manufacturing energy and the energy savings value are obtained from an economic payback time calculator of VSD manufacturer ABB [46]. The default value of the calculator of 8000 operating hours per year with the duty cycle of 35% of the time at 70% of the rated power and 65% of the time at 80% of the rated power were considered.

As described in the previous section, if we assume that 5% of the purchase cost of the VSD (4693 £ or around 95 £/kW) is attributed to the embodied energy and if the energy consumption of the motor-driven system given by the manufacturer before (260923 kWh) and after the VSD installation (161655 kWh) are inserted into (3) the power electronics energy payback time of the VSD (PE EPBT$_\mathrm{VSD}$) is as follows:

$$\begin{aligned}\text{PE EPBT}_\mathrm{VSD} &= \frac{\Delta(E_\mathrm{emb})_\mathrm{system}}{(\Delta E_\mathrm{loads})_\mathrm{system}/\mathrm{year}} \\ &= \frac{E_\mathrm{emb\_VSD}}{(E_\mathrm{loads\_fixspeed} - E_\mathrm{loads\_VSD})/\mathrm{year}} \\ &= \frac{5866\,\mathrm{kWh}}{260923\,\mathrm{kWh} - 161655\,\mathrm{kWh}} \cdot 12 \\ &= 0.7\,\mathrm{months}.\end{aligned} \tag{8}$$

It is important to note that it is assumed that the system will be retrofitted with a VSD, which means that $\Delta E_\mathrm{emb\_system} = E_\mathrm{emb\_VSD}$ while if it is a new installation $\Delta E_\mathrm{emb\_system}$ would

Fig. 9. PV power optimiser SolarMagic [59].

equal the difference between the embodied energies of the VSD $E_{\mathrm{emb\_VSD}}$ and the embodied energy of an alternative manner of controlling the output flow (for example a throttle $E_{\mathrm{emb\_throttle}}$) which would considerably reduce the payback time.

2) Photovoltaic Power Optimizers: When it comes to photovoltaic systems, the performance of a PV array is only as strong as its weakest performing panel. In case of building integrated photovoltaic (PV) systems average losses of about 20–25% in electricity production due to mismatching losses, partial shadows, variations in characteristics of PV modules due to manufacturing processes, differences in the orientations, and inclinations of solar surface etc. [34], [55], [56]. By introducing power electronic converters with advanced control and maximum power point tracking at the panel level the energy output of the array can be significantly improved [33], [56]–[58].

A case study chosen here includes SolarMagic power optimizers (Fig. 9) that maximize the energy potential of each individual panel so that as much as 50% of the lost energy can be reclaimed. These dc/dc converters with advanced control algorithms continuously track the individual maximum power of each panel, maintaining maximum array power and balance.

The benchmark system [59] is a 30 kW residential PV system consisting of 204 panels rated at 175 W each. By introducing power optimizers on 6 out of 17 strings (each string consists of 12 panels) an increase in the power output of 22.6% out of the same panels was achieved compared to before the installation of the optimizers. The power electronics energy payback time of such an optimizer is then as follows:

$$\begin{aligned}\text{PE EPBT}_{\mathrm{PV\_power\_opt}} &= \frac{\Delta(E_{\mathrm{emb}})_{\mathrm{system}}}{(\Delta E_{\mathrm{loads}})_{\mathrm{system}}/\mathrm{year}} \\ &= \frac{E_{\mathrm{emb\_PV\_power\_opt}}}{(E_{\mathrm{loads\_noopt}} - E_{\mathrm{loads\_withopt}})/\mathrm{year}} \\ &= \frac{163\,\mathrm{kWh}\cdot 72}{47000\,\mathrm{kWh}}\cdot 12 = 3\,\mathrm{months}. \quad (9)\end{aligned}$$

3) HID Lamp Electronic Ballast: High intensity discharge (HID) lamps have been widely used in lighting applications due to their superior properties such as high efficacy, good color rending and long life. Because of their negative incremental impedance, HID lamps must be operated in series with current controlled ballasts. In increasing demands for smaller size, smaller weight, and energy savings, magnetic ballasts have been substituted with electronic ballasts in many applications achieving typical energy savings of 10–25% [60], [61].

The case study compares the annual electricity consumption for magnetic and electronic ballast HID lighting systems in a typical warehouse installation [62]. The system consists of 100 metal halide HID lamps (each rated at 400 W) with magnetic ballasts and 87 lamps with electronic ballasts for the same system output lumens (2 650 000). In this example, the electronic ballast system provides a 22% reduction in the annual electricity use compared to the magnetic ballast system.

$$\begin{aligned}&\text{PE EPBT}_{\mathrm{HID\_el\_ballast}} \\ &\quad = \frac{\Delta(E_{\mathrm{emb}})_{\mathrm{system}}}{(\Delta E_{\mathrm{loads}})_{\mathrm{system}}/\mathrm{year}} \\ &\quad = \frac{E_{\mathrm{emb\_HID\_el\_ballast}}\cdot 87}{(E_{\mathrm{loads\_mag\_ballast}} - E_{\mathrm{loads\_el\_ballast}})/\mathrm{year}} \\ &\quad = \frac{25721\,\mathrm{kWh}}{69300\,\mathrm{kWh}}\cdot 12 = 4.4\,\mathrm{months}. \quad (10)\end{aligned}$$

Similar to the variable speed drive case study, it is assumed that the system will be retrofitted with electronic ballasts, which means that $\Delta E_{\mathrm{emb\_system}} = E_{\mathrm{emb\_el\_ballast}}$, while in the case of a new installation $\Delta \mathrm{E}_{\mathrm{emb\_system}}$ would equal the difference between $E_{\mathrm{emb\_el\_ballast}}$ and $E_{\mathrm{emb\_mag\_ballast}}$ which would considerably reduce the payback time.

B. Sustainable Energy Balance Reduction by Means of Power Electronics—Example

The previous section showed that the energy payback time of power electronics converters is short, especially compared to other subsystems in sustainable energy systems.

The next step is to get an idea of how much the introduction of power electronics reduces the sustainable energy balance of a system. Let us consider a system consisting of the PV panels from Section IV-A2 as renewable energy sources (two 30 kW systems consisting of 204 modules, each rated at 175 W) and the HID lighting system (100 lamps each rated at 400 W) from Section IV-A3. as the loads. We will investigate how the sustainable energy balance changes for four set-ups:

1) PV panels with no power optimizers powering HID lamps with magnetic ballasts;
2) PV panels with no power optimizers powering HID lamps with electronic ballasts;
3) PV panels with power optimizers powering HID lamps with magnetic ballasts;
4) PV panels with power optimizers powering HID lamps with electronic ballasts.

Table II shows the values of sustainable energy balance for all four cases. It can be seen that by introducing power electronic power optimizers on the panels and/or power electronic ballasts for the HID lights the sustainable energy balance of the system is greatly reduced. By introducing power electronics on the renewable source or the load side only, the time is reduced more than 1.5 times and by utilizing power electronics on both sides the time is reduced 2.5 times.

TABLE II
SUSTAINABLE ENERGY BALANCE FOR DIFFERENT SYSTEM CONFIGURATIONS: CASE STUDY

	PV system with no power optimisers HID lamps with magnetic ballasts	PV system with no power optimisers HID lamps with electronic ballasts	PV system with power optimisers HID lamps with magnetic ballasts	PV system with power optimisers HID lamps with electronic ballasts
Sustainable energy balance [years]	3.7	2.2	2	1.5

V. CONCLUSION

Power electronics is a key technology for a sustainable electrical energy future. Alongside renewable energy sources and energy efficient loads, power electronics is an enabler in sustainable energy systems which provide energy for the full life-cycle of electrical loads, including the energy for manufacturing and end-of-life management as well as the energy for their operational cycles. It is shown in this paper that power electronics can significantly reduce the time to achieve the sustainable energy balance of such systems.

The concept of energy payback time of power electronics is introduced in this paper and can be used as a powerful tool to quantify the contribution of power electronics to sustainability. From the life-cycle analysis performed on two power electronics converters it can be seen that the energy needed to manufacture the converters is practically negligible compared to the energy saved by introducing these converters in motor drive systems. This translates into a short energy payback time of power electronics.

From the presented case studies obtained it can be ascertained that the energy payback time of adding power electronics is in the range of a few months. In most cases this is considerably shorter or at least comparable to that of renewable energy sources (wind turbines 6–8 months, PV systems 1–3 years). Yet, the renewable energy sources are well known to the general public for their "green" epithet while few know about the energy savings potential of power electronics. The concept of power electronics energy payback time can be used to positively influence this perception. Since the implementation of power electronics has a multiplying effect (see Table II), this figure of merit can also be used as a powerful tool in illustrating the value of power electronics to both policy makers and the general public. This will help power electronics move forward and realize its full potential toward the sustainable energy future.

Looking at the complete energy life-cycle picture of the presented two converters, it can be concluded that the energy dissipated through losses during the converter's life is an order of magnitude larger than its embodied energy. Thus, further improvements in the total energy footprint of the converter should come from increasing the converter's conversion efficiency and only when this value is increased by a couple of percentage points compared to today's typical values will the embodied energy represent a significant part in the total picture.

ACKNOWLEDGMENT

The authors would like to thank ABB and Siemens AG Drive Technologies for providing the hardware and the data on the case study variable speed drives and Infineon Technologies AG for its help in assessing the embodied energy of power modules.

REFERENCES

[1] M. Z. Jacobson and M. A. Delucchi, "A path to sustainable energy by 2030," *Scientific Am.*, vol. 301, pp. 58–65, Nov. 2009.
[2] D. Divan and F. Kreikebaum, "Organic (but not green)," *IEEE Spectrum*, vol. 46, no. 11, pp. 47–49, Nov. 2009.
[3] L. M. Beard, J. B. Cardell, I. Dobson, F. Galvan, D. Hawkins, W. Jewell, M. Kezunovic, T. J. Overbye, P. K. Sen, and D. J. Tylavsky, "Key technical challenges for the electric power industry and climate change," *IEEE Trans. Energy Convers.*, vol. 25, no. 2, pp. 465–473, Jun. 2010.
[4] J. Arai, K. Iba, T. Funabashi, Y. Nakanishi, K. Koyanagi, and R. Yokoyama, "Power electronics and its applications to renewable energy in Japan," *IEEE Circuits Syst. Mag.*, vol. 8, no. 3, pp. 52–66, 2008.
[5] M. Matsuura, H. Shiroyama, and T. Suzuki, "Sustainable energy and environmental policymaking in Japan," *IEEE Technol. Soc. Mag.*, vol. 29, no. 3, pp. 45–54, Fall 2010.
[6] R. Harmon and H. Demirkan, "The next wave of sustainable IT," *IT Professional*, vol. 13, no. 1, pp. 19–25, Jan./Feb. 2011.
[7] C. J. Andrews, "Social implications of pursuing sustainability [Guest Editorial]," *IEEE Technol. Soc. Mag.*, vol. 29, no. 3, p. 13, Fall 2010.
[8] B. Norton, "Renewable electricity-what is the true cost?" *Power Eng. J.*, vol. 13, no. 1, pp. 6–12, Feb. 1999.
[9] P. Marwedel and M. Engel, "Plea for a holistic analysis of the relationship between information technology and carbon-dioxide emissions," in *Proc. 23rd Int. Conf. Architecture Comput. Syst. (ARCS),* Dortmund, Germany, 2010, pp. 1–6.
[10] International Energy Agency, IEA, [Online]. Available: www.iea.org
[11] International Energy Outlook 2009, [Online]. Available: www.eia.doe.gov
[12] Eurostat, [Online]. Available: http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables
[13] B. Bose, "Global warming: Energy, environmental pollution, and the impact of power electronics," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 6–17, Mar. 2010.
[14] B. Kroposki, C. Pink, R. DeBlasio, H. Thomas, M. Simoes, and P. K. Sen, "Benefits of power electronic interfaces for distributed energy systems," *IEEE Trans. Energy Convers.*, vol. 25, no. 3, pp. 901–908, Sep. 2010.
[15] P. K. Steimer, "Enabled by high power electronics - Energy efficiency, renewables and smart grids," in *Proc. 2010 Int. Power Electron. Conf. (IPEC)*, Sapporo, Japan, pp. 11–15.
[16] G. Spagnuolo, G. Petrone, S. V. Araujo, C. Cecati, E. Friis-Madsen, E. Gubia, D. Hissel, M. Jasinski, W. Knapp, M. Liserre, P. Rodriguez, R. Teodorescu, and P. Zacharias, "Renewable energy operation and conversion schemes: A summary of discussions during the seminar on renewable energy systems," *IEEE Ind. Electron. Mag.*, vol. 4, no. 1, pp. 38–51, Mar. 2010.
[17] *Electronics Enabling Efficient Energy Usage* [Online]. Available: http://www.e4efficiency.eu/
[18] Cool Earth – Innovative Energy Technology Program. Ministry of Economy, Trade and Industry, Japan, March 2008.

[19] BMBF Programme ICT2020, *Power electronics to improve energy efficiency*, [Online]. Available: http://www.bmbf.de/foerderungen/13123.php

[20] *Towards an ICT infrastructure for energy positive neighbourhoods,* ELSA Thematic Working Group on ICT for energy efficiency, (2009, Oct.) [Online]. Available at: http://ec.europa.eu/information_society/activities/sustainable_growth/docs/elsa/elsa_report/ELSA-EnergyPositive-Report1.pdf 2011.

[21] *European Technology Platforms* [Online]. Available: http://cordis.europa.eu/technology-platforms/

[22] K. E. Knapp, T. L. Jester, and G. B. Mihaiik, "Energy balances for photovoltaic modules: Status and prospects," in *Conf. Rec. 28th IEEE Photovoltaic Spec. Conf., 2000*, pp. 1450–1455.

[23] R. H. Crawford, G. J. Treloar, R. J. Fuller, and M. Bazilian, "Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit," *Renewable and Sustainable Energy Rev.*, vol. 10, no. 6, pp. 559–575, Dec. 2006.

[24] S. Krohn, "The energy balance of modern wind turbines," *Wind Power Note*, vol. 16, pp. 1–16, Dec. 1997.

[25] L. Gagnon, C. Be´ langer, and Y. Uchiyama, "Life-cycle assessment of electricity generation options: The status of research in year 2001," *Energy Policy*, vol. 30, no. 14, pp. 1267–1278, Nov. 2002.

[26] E. Martinez, F. Sanz, S. Pellegrini, E. Jimenez, and J. Blanco, "Life cycle assessment of a multi-megawatt wind turbine," *Renewable Energy*, vol. 34, pp. 667–673, 2009.

[27] M. Lenzen and J. Munksgaard, "Energy and CO_2 life-cycle analyses of wind turbines—Review and applications," *Renewable Energy*, vol. 26, no. 3, pp. 339–362, Jul. 2002.

[28] R. Barthelmie, "Wind energy: Status and trends," *Geography Compass*, vol. 1, pp. 275–301, 2007.

[29] The British Wind Energy Association (BWEA), [Online] Available: http://www.bwea.com

[30] M. Ito, K. Kato, K. Komoto, T. Kichimi, and K. Kurokawa, "A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules," *Progress Photovoltaics: Res. Appl.*, vol. 16, pp. 17–30, Jan. 2008.

[31] V. Fthenakis and E. Alsema, "Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status," *Progress Photovoltaics: Res. Appl.*, vol. 14, pp. 275–280, 2006.

[32] *Action plan for energy efficiency: Realising the potential*. European Commission, Brussels (2006, Oct. 19), [Online]. Available: http://ec.europa.eu/energy/action_plan_energy_efficiency/doc/com_2006_0545_en.pdf

[33] Z. Liang, R. Guo, J. Li, and A. Q. Huang, "A high-efficiency PV module-integrated dc/dc converter for PV energy harvest in FREEDM systems," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 897–909, Mar. 2011.

[34] E. Roman, R. Alonso, P. Ibanez, S. Elorduizapatarietxe, and D. Goitia, "Intelligent PV module for grid-connected PV systems," *IEEE Trans. Ind. Electron.*, vol. 53, no. 4, pp. 1066–1073, Jun. 2006.

[35] J. B. Guinée, M. Gorrée, R. Heijungs, G. Huppes, R. Kleijn, A. de Koning, L. van Oers, A. Wegener Sleeswijk, S. Suh, H. A. Udo de Haes, H. de Bruijn, R. van Duin, and M. A. J. Huijbregts, *Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards*. Norwell, MA: Kluwer Academic Publishers, 2002.

[36] H.-J. Althaus, C. Bauer, G. Doka, R. Dones, R. Hischier, S. Hellweg, S. Humbert, T. Kollner, Y. Loerincik, M. Margni, and T. Nemecek. (2007, Dec. 3) *Implementation of Life Cycle Impact Assessment Methods Data v2.0* [Online]. Available: http://www.ecoinvent.org/fileadmin/documents/en/03_LCIA-Implementation.pdf

[37] I. Boustead and G. F. Hancock, *Handbook of Industrial Energy Analysis*. Chichester, West Sussex, U.K.: Ellis Horwood Ltd., 1979.

[38] Eco-invent, [Online] Available: http://www.ecoinvent.org/

[39] Idemat, [Online] Available: http://www.idemat.nl/

[40] Inventory of Carbon & Energy, Version 2.0 [Online]. Available: www.bath.ac.uk/mech-eng/sert/embodied/

[41] *Cambridge Engineering Selector*, [Online]. Available: http://www-edc.eng.cam.ac.uk/tools/ces

[42] *Eco-costs value*, [Online]. Available: http://www.ecocostsvalue.com/index.html

[43] Powerex Power Semiconductors, [Online] Available: www.pwrx.com

[44] Eric R. Motto, "New converter-inverter-brake (CIB) module and matching high voltage integrated circuit (HVIC)," *Motor and Drive Syst.*, pp. 1–22, 2007.

[45] Semikron, [Online] Available: www.semikron.com

[46] *Loan calculator shows energy saving profit* [Online]. Available: http://www.abb.com/cawp/seitp202/4E6569F71DE76CB180256D0A004BA9E8.aspx

[47] R. Bahadur and A. Bar-Cohen, "Thermal design and optimization of natural convection polymer pin fin heat sinks," *IEEE Trans. Componen. Packag. Technol.*, vol. 28, no. 2, pp. 238–246, Jun. 2005.

[48] O. Perpiñan, E. Lorenzo, M. A. Castro, and R. Eyras, "Energy payback time of grid connected PV systems: Comparison between tracking and fixed systems," *Progress in Photovoltaics: Res. Appl.*, vol. 17, pp. 137–147, 2009.

[49] M. J. de Wild-Scholten, E. A. Alsema, E. W. ter Horst, M. Bächler, and V. M. Fthenakis, "A cost and environmental impact comparison of grid-connected rooftop and ground-based PV systems," in *Proc. 21st Eur. Photovoltaic Solar Energy Conf.*, Dresden, Germany, 2006.

[50] J. E. Mason, V. M. Fthenakis, T. Hansen, and H. C. Kim, "Energy payback and life-cycle CO2 emissions of the BOS in an optimized 3·5MW PV installation," *Progress Photovoltaics: Res. Appl.*, vol. 14, pp. 179–190, 2006.

[51] J. A. Rooks and A. K. Wallace, "Energy efficiency of VSDs," *IEEE Ind. Appl. Mag.*, vol. 10, no. 3, pp. 57–61, May/Jun. 2004.

[52] *Major trend energy efficiency* (2008), *Power Electronics Europe,* no. 5, pp. 12–16. [Online]. Available: http://www.power-mag.com/pdf/issuearchive/24.pdf

[53] J. Reinert, "Improving performance and energy consumption of industrial processes by using variable speed drives," in *Proc. ECPE Seminar Towards Energy Gain and Savings—Emerging Drives and Generator Systems*, Warsaw, Poland, 2008.

[54] A. De Almeida, *VSDs for electric motor systems*. Brussels, Belgium: European Commission – DG TREN, Dec. 2001.

[55] M. C. Alonso-Garcíaa, J. M. Ruizb, and F. Chenlo, "Experimental study of mismatch and shading effects in the I–V characteristic of a photovoltaic module," *Solar Energy Mater. Solar Cells*, vol. 90, no. 3, pp. 329–340, Feb. 2006.

[56] *Analysis of Photovoltaic Systems*. Paris, France: Int. Energy Agency—Photovoltaic Power Systems Program, 2000.

[57] Y.-H. Ji, D.-Y. Jung, J.-G. Kim, J.-H. Kim, T.-W. Lee, and C.-Y. Won, "A real maximum power point tracking method for mismatching compensation in PV array under partially shaded conditions," *IEEE Trans. Power Electron.*, vol. 26, no. 4, pp. 1001–1009, Apr. 2011.

[58] G. R. Walker and P. C. Sernia, "Cascaded dc-dc converter connection of photovoltaic modules," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 1130–1139, Jul. 2004.

[59] *SolarMagicTM reclaims lost energy, boosts power production from normally-operating array by 22.6%* [Online]. Available: http://solarmagic.com/en/files/SolarMagic_CaseStudy_OakStreet.pdf

[60] E. Mills and M. A. Piette, "Advanced energy-efficient lighting systems: Progress and potential energy," *Energy-Efficient Lighting*, vol. 18, no. 2, pp. 75–97, Feb. 1993.

[61] H. S.-H. Chung, N.-M. Ho, W. Yan, P. W. Tam, and S. Y. Hui, "Comparison of dimmable electromagnetic and electronic ballast systems—An assessment on energy efficiency and lifetime," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3145–3154, Dec. 2007.

[62] [Online] Available: http://oee.nrcan.gc.ca/industrial/equipment/lighting/savings.cfm?attr=24

Jelena Popović-Gerber (S'04–M'05) received the Dipl.-Ing. degree from the Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia, in 2001, and the Ph.D. degree from the Delft University of Technology, Delft, The Netherlands, in 2005.

From 2005 to 2011, she was with European Center for Power Electronics (ECPE), earlier as a Technology Transfer Coordinator for one of the ECPE demonstrator programs "Industrial Drives – System Integration," and later worked on various strategic activities related to power electronics enabled energy efficiency including the setting up of the European Technology and Innovation Platform "Electronics for Energy Efficiency and Sustainability (EEESy)." Since 2008, she has been with the Delft University of Technology as an Assistant Professor in Power Electronics. Her research interests include packaging and integration in power electronics and energy efficiency enabled by power electronics.

Jan Abraham Ferreira (M'98–SM'01–F'05) was born in Pretoria, South Africa, and received the B.Sc. Eng.(cum laude), M.Sc. Eng.(cum laude), and Ph.D. degrees in electrical engineering from the Rand Afrikaans University, Johannesburg, South Africa.

In 1981, he did research on battery vehicles at the Institute of Power Electronics and Electric Drives, Technical University of Aachen, and worked in industry as a Systems Engineer at ESD (Pty) Ltd from 1982–1985. From 1986 until 1997, he was at the Faculty of Engineering, Rand Afrikaans University, where he held the Carl and Emily Fuchs Chair of Power Electronics in later years. In 1998, he became Professor of power electronics and electrical machines at the Delft University of Technology, The Netherlands. During 1993–1994, he was Chairman of the South African Section of the IEEE. He is the founding chairman of the IEEE Joint IAS/PELS Benelux chapter. He served in 1995–1996 as the Chairman of the IEEE IAS Power Electronic Devices and Components Committee. He is an Associate Editor of the *PELS Transactions* and served as Treasurer and Vice President at the meetings of the IEEE PELS.

Dr. Ferreira was Chairman of the CIGRE SC14 National Committee of The Netherlands, from 1999–2002, and is a member of the Executive Committee of the European Power Electronic Association EPE Society (1999–2003; 2008–till date).

Jacobus Daniel van Wyk (S'00–A'03) received the M.Sc. (Eng.) degree from the University of Pretoria, South Africa, in 1966, the Dr. Sc.(tech.) degree from the Technical University of Eindhoven, The Netherlands, in 1969, an honorary D.Sc. (Eng.) degree from the University of Natal, South Africa, in 1996, and an honorary D.Eng degree from the University of Pretoria, South Africa, in 2008.

He has worked with the S.A. Iron and Steel Corporation, the University of Pretoria, and with the technical and scientific staff of the University in Eindhoven, between 1961 and 1971. From 1971 to 1995, he was a chaired Professor of electrical and electronic engineering at the Rand Afrikaans University, Johannesburg, holding chairs in electronics and in power electronics till 1992. He founded the Industrial Electronics Technology Research Group in the Faculty of Engineering, in 1978, and directed it until 1999. From 1995 to 2004, he held a special University Research Chair in Industrial Electronics at the Rand Afrikaans University. He joined the Bradley Department of Electrical and Computer Engineering at the Virginia Polytechnic Institute and State University, Blacksburg, VA, in 1999, where he was the J. Byron Maupin Professor of Engineering from 2000 until his retirement in 2005. At Virginia Tech he was with the National Science Foundation Engineering Research Center for Power Electronics Systems, leading the research on high density integration until July 2006. From 2006 to 2008, he was a research faculty member in the Center, and is at present a Visiting Professor at the University of Johannesburg. He has been author and coauthor of more than 600 publications, receiving 23 publication awards for his works, including 15 IEEE prize paper awards.

Dr. van Wyk was the recipient of the prestigious IEEE William E. Newell Power Electronics Award in 1995, an IEEE Third Millennium Medal in 2000, the IEEE Power Electronics Society Distinguished Service Award in 2006, and the IEEE Industry Applications Society Outstanding Achievement Award in 2006. He has received a range of other awards from IEEE Societies, the South African Institute of Electrical Engineers and other organizations and was Editor-in-Chief of the IEEE TRANSACTIONS ON POWER ELECTRONICS from 2002 to 2006. He is a Fellow of the South African Institute of Electrical Engineers.