



# Environmental Criteria Optimization of a Power Module

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**Objective** – This contribution integrates the environmental aspect into the design criteria by examining the implications for the choice of power components. Sizing criteria are selected as optimization variables. The power module is considered as an application case.

**Findings** – The results indicate that the selection of the current rating to maximize efficiency is not always in alignment with minimizing environmental impacts. A sensitivity analysis was conducted to assess the impact of variations in the operating cycle and energy mix on the results.

**Originality** – This work presents novel parametric models founded upon Life Cycle Analysis, which are utilized to quantify the environmental impacts associated with voltage and current ratings. This model incorporates aging and failure as a consequence of the selected parameters within a unique context of circularity, emphasizing replacements.

**Keywords** – Power electronics, Eco-design, Optimization, Life Cycle Analysis, Environmental Impact, Sensibility Analysis

## 1. Introduction

Electrical engineering devices play a crucial role in energy transition. Their use tends to become widespread, and their number is growing rapidly, which can lead to significant pollution and hinder environmental transition. In response to this observation, how can power electronics be rethought to reduce their environmental footprint, while protecting biodiversity and social aspects?

To meet these challenges, various strategies and actions can be considered. Sustainability research targets several key areas, including:

- Energy efficiency: Designers aim to maximize energy efficiency by minimizing structural energy losses and optimizing power converter management.
- Material selection: Careful consideration is given to the materials used, with a preference for recyclable materials and a reduction in the use of environmentally harmful substances, such as lead, mercury, and cadmium.
- Manufacturing, assembly, and disassembly processes: Manufacturing processes are optimized to be more sustainable by reducing energy consumption, minimizing waste, and promoting efficient disassembly and recycling practices.
- Sizing: Dimensional parameters are adjusted for an eco-optimization approach, maximizing functional criteria while minimizing environmental impacts over the life cycle.
- Reliability: Designers aim to extend the lifespan of power electronics products to limit the need for replacement and re-manufacturing. Effective thermal management can also extend the lifespan of systems.
- Repairability: Efforts are made to improve the repairability of power electronics by designing modular products and simplifying repair processes.

Once these initiatives are implemented, it is crucial to conduct a quantitative assessment of the environmental benefits using the Life Cycle Analysis (LCA) tool. This approach allows verifying whether the proposed solution actually leads to

environmental improvement and avoiding rebound effects. Naturally, this tool can also be used independently of the eco-design process to analyze the Environmental Impacts (EI) of a product.

There is an intrinsic link between eco-design and optimization, which lies in the search for an ideal solution, both in terms of functionality and environmental sustainability. Eco-design aims to integrate environmental considerations from the earliest stages of development, while "standard" optimization focuses on finding the optimal parameters to achieve maximum technical and/or economic performance. In the field of Power Electronics (PE), optimization can help minimize EI by adjusting various parameters, such as ratings, dimensions, materials, or operating modes. This approach makes it possible to reach the point of optimal operational performance and maximum reduction of EI. It is based on a rigorous assessment of environmental impacts through an LCA. Figure 1 presents the process for an eco-optimized system.

The objective of this paper is to integrate the environmental aspect into the design criteria by examining the implications on the choice of power components. Sizing criteria are selected as optimization variables. For this analysis, only the power module part is considered. This raises the question of whether it is more appropriate to oversize the system, potentially leading to an increase in manufacturing-related EI, but a decrease in these impacts during use, or to undersize, which would reduce EI during manufacturing, increase them during use, and also risk increasing failures and replacements. Figure 2 illustrates this issue.

The paper describes two parts: the first one sets up the optimization problem, with the choice of variables, the different models, and proposes a metric for selecting the optimal solution. The second part presents the results of the optimization with the implementation of a sensitivity study.

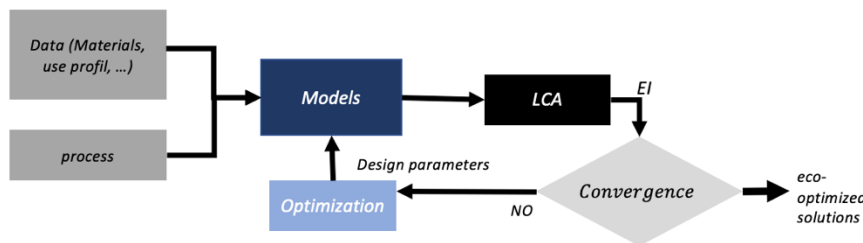


Figure 1 – Eco-optimization process

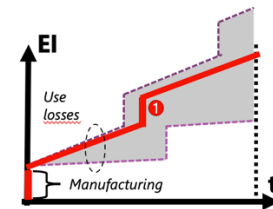


Figure 2 – Evolution of an environmental impact of a component over time.

## 2. Formalization of the eco-optimization problem

The first step of the optimization is to select performance criteria, and in the context of eco-optimization, the objective is to minimize, under constraints, the total environmental cost. The chosen criteria are therefore the EI on life cycle.

Regarding the optimization variables, it seems relevant to choose characteristic parameters of a power module, which are the current rating  $I_k$  and voltage rating  $V_k$ . It is indeed possible to determine the dimensions, volumes and compositions of the components from these two ratings, and therefore to develop parametric EI models in the final paper.

Regarding the constraints, it is essential to respect the actual limits of a power module. First, a current limit related to excessive heating caused by conduction and switching losses. The second limit concerns the voltage, where it is essential to avoid exceeding the avalanche voltage (breakdown voltage), which represents the maximum voltage that the components can withstand without causing a short circuit or a failure due to the rupture of the insulation between the gate and the other parts of the device. As an example, for the reference power module (750V - 820A IGBT module), the maximum allowable junction temperature is 175°C and the maximum voltage of the recommended safe operating area is 750V, which ensures operation without going into avalanche during switching, which would damage the component.

The problem can therefore be expressed as follows:

$$\min_{I_k, V_k} \sum_n \rho_n \frac{EI_n(I_k, V_k)}{EI_{nref}} \quad (1)$$



The total life cycle EI corresponds to the sum of the EI during manufacturing, use, and replacement. These three categories of EI are modeled as a function of the optimization variables. They depend in particular on the losses generated and the aging (cycling and calendar) of the components.

$\rho_n$  is a weighting factor for each type of impact,  $E_{I_{ref}}$  is the reference value of the impact considered [7].

## 2.1 Parametric models of EI

From the values obtained from the EcolInvent database [14] and the indications given in [8], we have constructed parametric LCA models for the power module.

Thus, Figure 3 shows some points and the linear models adopted for each environmental impact associated with the manufacturing phase (Environmental impacts are shown in table 2).

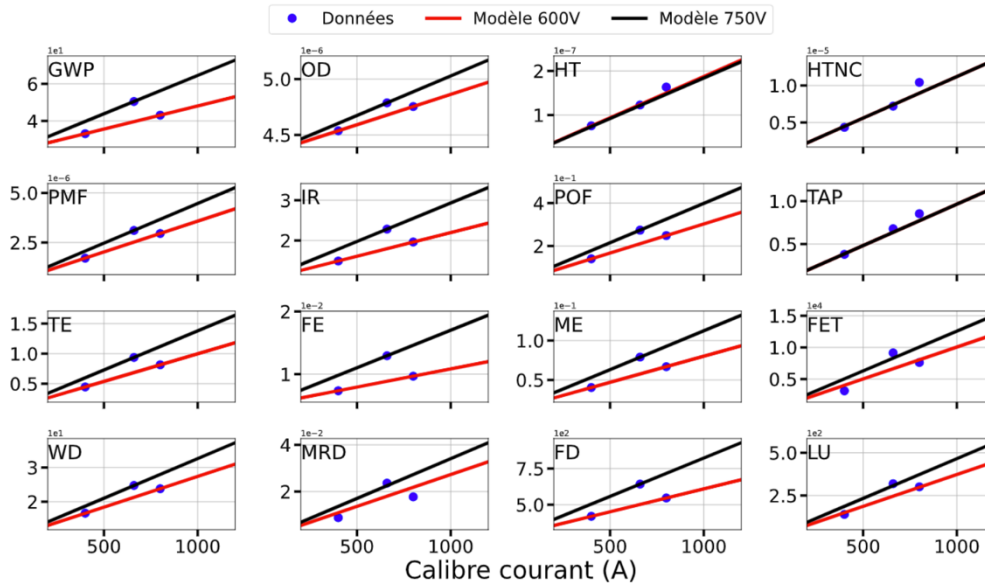


Figure 3 – EI data for the manufacturing of reference power modules and corresponding models  
 $EI(e) f = f(I_k, V_k)$

The identified model is written as:

$$EI_f^{(e)}(I_k, V_k) = (a \cdot V_k + b)I_k + c \quad (2)$$

The coefficients a, b, and c considered are given in Table 1.

Table 1. Values of the model coefficients

	<b>GWP</b>	<b>OD</b>	<b>HT</b>	<b>HTNC</b>	<b>PMF</b>	<b>IR</b>	<b>POF</b>	<b>TAP</b>
<b>a</b>	1.10E-04	1.10E-12	-2.11E-14	0.00E+00	5.93E-12	4.90E-06	6.38E-07	0.00E+00
<b>b</b>	-4.09E-02	-1.18E-10	2.00E-10	1.12E-08	-4.49E-10	-1.77E-03	-1.12E-04	9.64E-04
<b>c</b>	23.1858652	4.32E-06	0	0	4.71E-07	1.01985992	0.03189291	0
	<b>TE</b>	<b>FE</b>	<b>ME</b>	<b>FET</b>	<b>WD</b>	<b>MRD</b>	<b>FD</b>	<b>LU</b>
<b>a</b>	2.55E-06	4.12E-08	2.15E-07	1.68E-02	3.48E-05	4.55E-08	1.42E-03	6.21E-04
<b>b</b>	-6.09E-04	-1.89E-05	-6.30E-05	0.00E+00	-2.90E-03	0.00E+00	-5.35E-01	0.00E+00
<b>c</b>	0.0776839	0.005038452	0.01386593	0	9.44777693	0	292.743623	0

Regarding the use phase, the EI are given by:

$$EI_u^{(e)}(I_k, V_k) = E_{losses}(I_k, V_k) \cdot EI_{1kWh}^{(e)} \quad (3)$$

These impacts depend directly on the losses during the operating phase ( $E_{losses}$ ) and on the  $EI_{1kWh}^{(e)}$  corresponding to the EI generated using 1kWh of energy according to the energy mix considered.



The losses are those classically generated by switching and conduction in the IGBTs and antiparallel diodes, assuming that the supply currents of the electric machine are sinusoidal.

This loss model is constructed from parameters specific to the component, the threshold voltages ( $V_{ce0}$ ,  $V_f$ ), the electrical resistances ( $R_{ce}$ ,  $R_f$ ) and the switching energies ( $E_{on+off}$ ,  $E_{rr}$ ). These parameters vary according to the current rating and voltage rating. Moreover, they are available directly in the component datasheets and have been used to derive empirical models from them.

Regarding the end-of-life phase, the associated impact ( $EI_r$ ) is expressed as follows:

$$EI_r^{(e)}(I_k, V_k) = EI_f^{(e)}(I_k, V_k) \cdot N_r^{\square}(I_k, V_k) \quad (4a)$$

$$N_r^{\square}(I_k, V_k) = \left( \left\lfloor \frac{t_{use}}{t_{life}} \right\rfloor - 1 + N_{E,R} \right) \quad (4b)$$

With  $t_{use}$  the usage duration,  $t_{life}$  the lifetime,  $N_r$  the number of replacements and  $N_{E,R}$  the number of replacements related to the youth period (E) and useful life (R). The quotient  $\lfloor t_{use}/t_{life} \rfloor$  gives a non-integer number for the number of replacements. It is assumed that  $N_{E,R}$  is not related to the different ratings.

It has been shown [9] that the failure rate in electronics follows a curve known as the "bathtub curve" [10], with the youth phase (design, poorly controlled manufacturing), the useful life (random failure), and aging (wear).

A probabilistic model based on the Weibull distribution has been adopted to generate defects. The defect related to thermal cycling aging depends on the thermal cycling, which in turn depends on the loss profile in the power module. The approach to generating probabilistic defects using a Monte Carlo method (here, 1000 draws are made) is relatively complex. Figure 4 illustrates the general approach. The reader is referred to [11] for details.

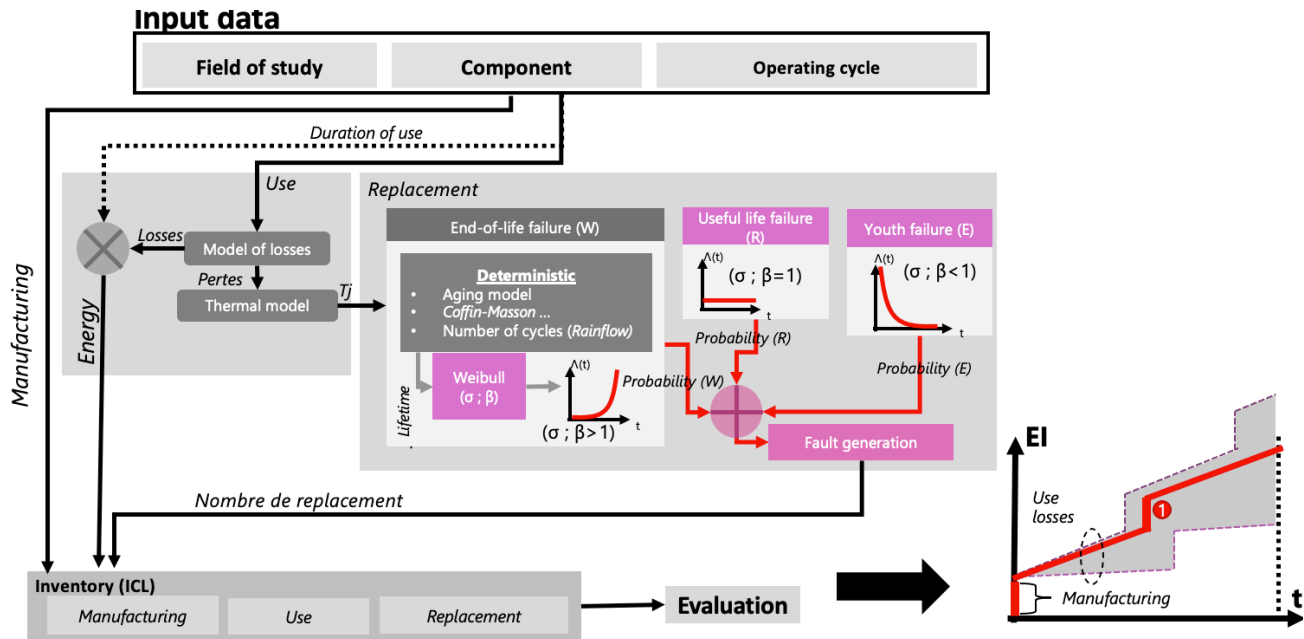


Figure 4 – Calculation of environmental impacts over the life cycle with consideration of replacement.

## 2.2 General Methodology

The general methodology for eco-optimizing the sizing consists, for each configuration of the parameters ( $V_k$ ,  $I_k$ ), in evaluating and then minimizing the environmental impacts  $EI$  associated with each life phase according to the parametric models described previously. The usage cycle considered is the standardized WLTP cycle.

The operating cycle is constructed from the standardized driving cycles (WLTP) of 1800 seconds duration, an electrical model of the machine (wound rotor MS, 59 kW, 4 pole pairs) and control allow the calculation of the armature currents and voltages. From these currents and voltages, an electrothermal simulation makes it possible to determine the junction temperature profile.

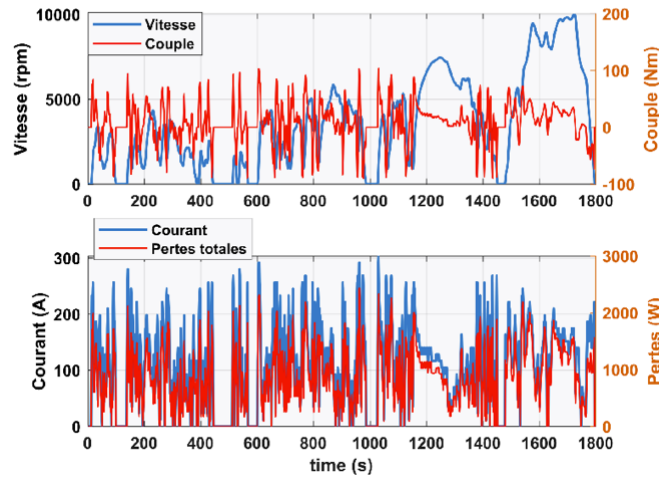


Figure 5 – Profiles of speed, torque, armature current, and losses in the inverter associated with a standardized WLTP cycle.

The losses cause an increase in temperature. These heat flows are dissipated by conduction to the heat sink. A coolant fluid conveys the heat by convection to the cooler. The different layers have thermal resistances and thermal capacities. A Foster-type model [12] is used to describe the thermal behavior of the system and is illustrated in Figure 6. The values of the thermal resistances and capacities are specific to the component and are provided by the manufacturer for each voltage and current rating.

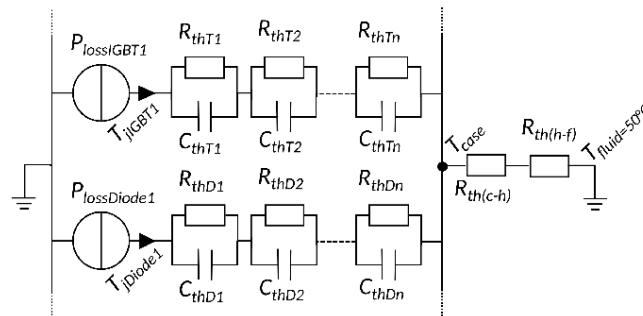


Figure 6 – Equivalent thermal model (only one IGBT-Diode module out of the six is represented).

Component replacement due to failure (youth phase, useful life and ageing) is determined using the method described in 2.1 above.

### 3. Results

The case study considered in this paper is an integrated three-phase IGBT power module. The functional unit corresponds to three-phase AC operation for a 50 kW load from a 450 V DC bus over a usage duration of 30 years. The operating cycle is the WLTP cycle with a duration of 660 h/year. The cooler (heat sink) is water-cooled with a thermal conductivity of 1500 W/m<sup>2</sup>K and a thermal resistance between the base and the coolant of 0.06 K/W. The energy mix considered is the global mix.

The environmental impacts chosen are sixteen in number and are specified in Table 2.



Table 2. Environmental impacts considered

Climate change	GWP	Ecotoxicity, freshwater	FET
Ozone depletion	OD	Water use	WD
Resource use, fossil fuels	FD	Eutrophication, freshwater	FE
Human toxicity, cancer	HT	Eutrophication, marine	ME
Human toxicity, non-cancer	HTNC	Acidification	TAP
Particulate matter	PM	Eutrophication, terrestrial	TE
Ionizing radiation	IR	Resource use, minerals, and metals	MRD
Photochemical ozone formation	POF	Land use	LU

### 3.1 Case of a fixed sizing

In this first study, we focus on a specific case of the power module FS820R08A6P2B HybridPACK Drive (Figure 7) [13].

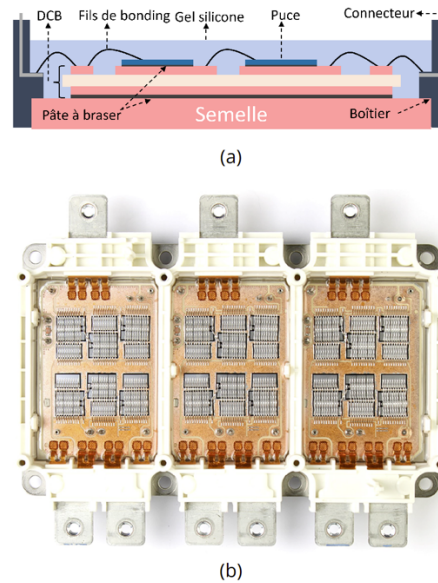


Figure 7 – (a) Cross-sectional view of the power module; (b) Interior view of a FS820R08A6P2B HybridPACK Drive [13].

The "cradle-to-gate" results are given in Figure 8. They show that two hotspots can be highlighted, namely: the chips and the baseplate. The baseplate has the greatest impact for human toxicity, with and without cancer (59% and 74%), acidification (63%), terrestrial eutrophication (39%), ecotoxicity (61%), mineral resource depletion (49%), and land use (54%). The fabrication of the chips has the main impact for: climate change (65%), ozone layer depletion (93%), fine particle emissions (39%), ionizing radiation (65%), photochemical ozone formation (36%), freshwater and marine eutrophication (69% and 43%), water consumption (56%), and fossil resource consumption (65%).

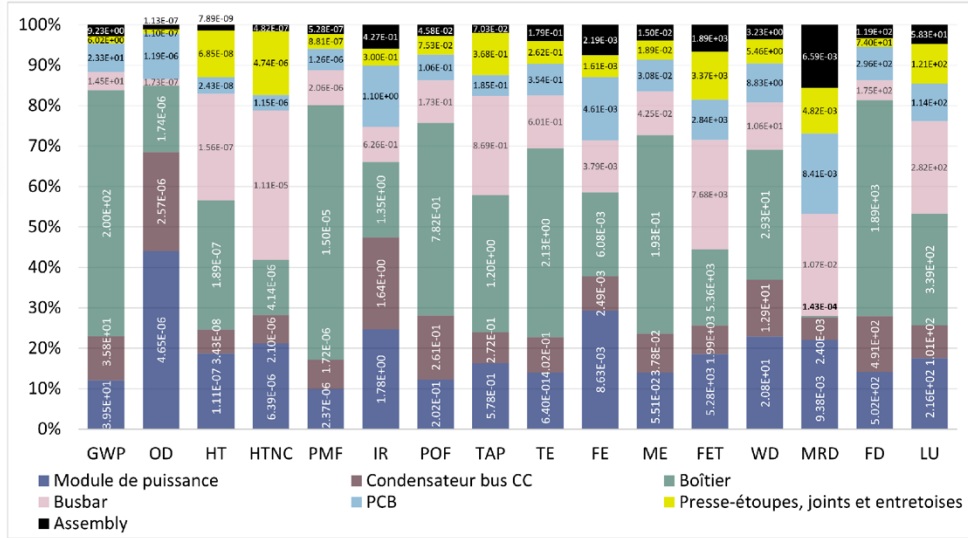


Figure 8 – "Cradle-to-gate" environmental impacts of the IGBT module FS820R08A6P2B. This result translates the normalized environmental impacts

### 3.2 Rating Optimization

Figure 9a presents the evolution of the global EI over the life cycle for manufacturing (defined by eq. 1), use, and replacement for different voltage ratings, with the current rating equal to 660A. The shape of the curves is explained by the manufacturing, use, and replacement models presented previously. The EI for manufacturing remains constant as a function of the rating, while that for use increases linearly. This leads, with the lifetime model and the increase in losses, to a non-linear increase in the number of replacements. Thus, the optimum for losses and over the life cycle corresponds to the choice of the lowest possible voltage rating, as increasing the voltage rating results in an increase in losses, manufacturing costs, and a decrease in reliability. Of course, there are also minimum value constraints to consider (avalanche). Figure 9b, on the other hand, presents the influence of the current rating on the global EI.

Regarding manufacturing, increasing the current rating results in a linear increase in EI for manufacturing. For the use phase, losses decrease with increasing rating until an optimum is reached, beyond which losses begin to increase again. The replacement phase is more complex due to the loss and thermal models; replacement decreases with increasing rating. Thus, there is an optimum related to the three curves. In cases where the EI related to manufacturing are weakly impacting, the optimum tends to approach that of the losses.

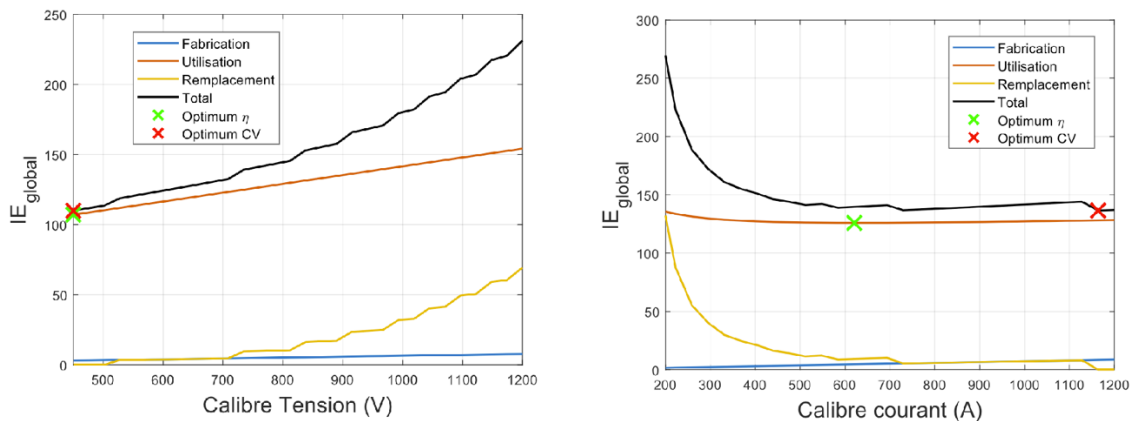


Figure 9 – Variation of the overall EI as a function of voltage rating (a, 660 A) and current rating (b, 750 V). Integrated power module following a WLTP operating cycle of 666 h/year, global energy mix over a usage duration of 30 years.



Figure 10a presents the confrontation between the overall EI and the losses in use for different current ratings, with the voltage rating fixed at 450V. This curve illustrates the fact that the choice to maximize efficiency is not always in favor of minimizing EI, thus creating a sort of Pareto front with the point at 830A that maximizes efficiency and the point at 610A that minimizes the overall EI. For a reduced operating duration, Figure 10b, (divided by 10), the overall EI is thus reduced by almost the same factor. Note that the current rating minimizing the overall EI is lower (ratio 2), while that maximizing efficiency remains unchanged.

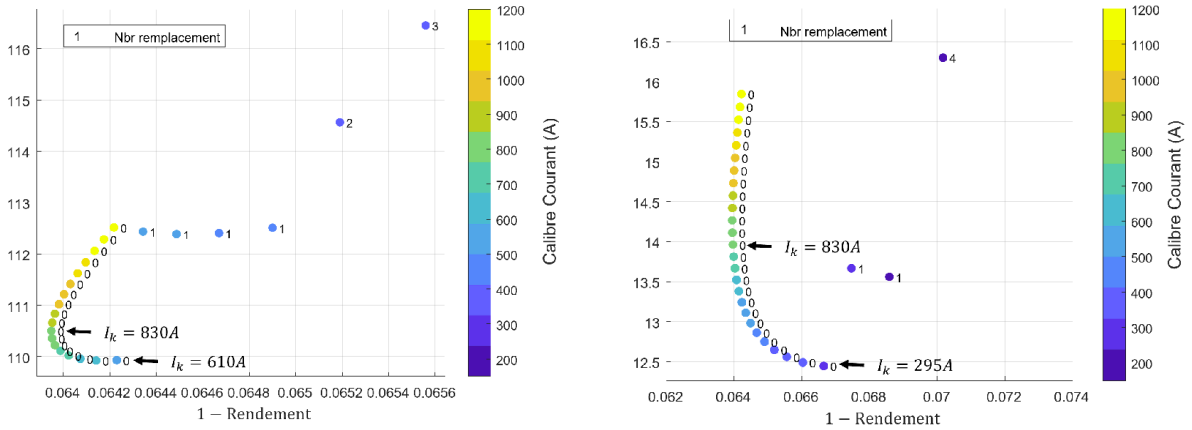


Figure 10 – (a) Variation of overall EI (weighted and normalized) as a function of 1- efficiency (losses) for a voltage rating of 450V. Integrated power module following a WLTP operating cycle of 666h/year (curve a) and WLTP 66h/year (curve b), global energy mix over a usage duration of 30 years. The figures indicate the number of replacements required.

### 3.3 Effect of the heat sink

Figure 11b illustrates the evolution of the EI of the power module and the cooler (photo 11a) as a function of variations in the thermal resistance ( $R_{th}$ ) of the cooler, over a usage duration of 30 years.

For the EI of the power module, increasing  $R_{th}$  leads to an increase in temperatures, the number of failures, and consequently the EI. Conversely, decreasing  $R_{th}$  (improving cooling) allows for a reduction in failures, until a point is reached where they no longer occur during the usage cycle (here at -20%). Regarding the cooler,  $R_{th}$  is inversely proportional to the EI, which means that reducing it results in an increase in mass and, consequently, the EI, until a point is reached where they become predominant. Thus, there is an optimum corresponding to the best compromise between the EI of the cooler and the EI related to the replacement of the module. This optimum is the one that allows for obtaining zero failures over the usage cycle, because the increase in the EI of the cooler occurs significantly only for a strong decrease in  $R_{th}$ . Unlike cycling defects, which in this case disappear for a slight variation.

In a more general conclusion, it appears that the design of the cooler must allow for avoiding failures related to the wear of the system.

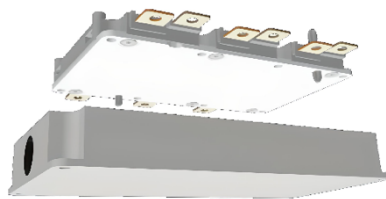


Figure 11 – View of the cooler with the IGBT power module.

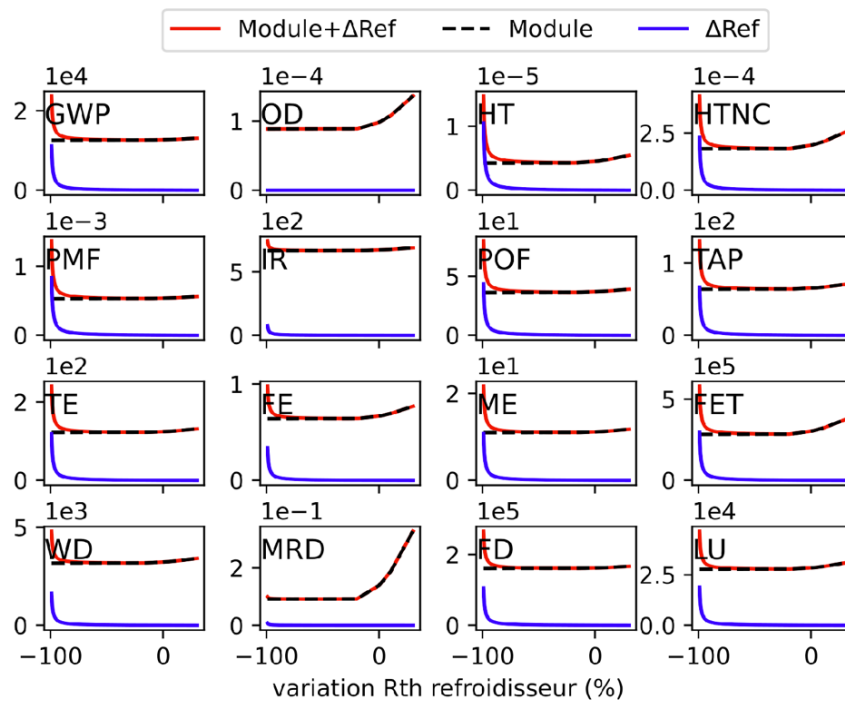


Figure 12 – Impact of the variation of the  $R_{th}$  of the cooler on the EI of the power module coupled with the variation of the EI of the cooler alone. The dashed curve represents the EI at 30 years of the power module (use + manufacturing/replacement), the red curve represents the variation of the EI related to the manufacturing of the cooler, and the blue curve represents the sum of the two.

## 4. Conclusion

Eco-optimization, which aims to find an optimal solution over the life cycle by integrating environmental parameters into the design process. The power module is the main object of study, with the current rating and voltage rating as optimization variables, useful for PE designers.

Different models have been developed to consider the optimization variables as well as the EI at various stages of the life cycle, including manufacturing, use, and replacement. The results obtained have revealed a conclusion: the optimum over the life cycle does not necessarily coincide with the optimum in operation, which favors maximum efficiency. In fact, each EI has its own optimum over the life cycle. Consequently, a metric has been suggested to select the optimal solution in terms of current rating and voltage rating, using the global EI which integrates the weighting and normalization of all EI.

The consideration of environmental parameters in the design of a PE system leads to distinct design choices. For example, if the environmental cost of manufacturing is high, the optimum could be a lower rating, approaching a limit where losses increase considerably. If the losses are high, the life cycle optimum approaches that of operation.

Furthermore, an in-depth analysis of the impact of the operating cycle, the duration of use, and the energy mix was carried out. The results highlight that for a system with low usage, with an undemanding operating cycle or a "decarbonized" energy mix, maximizing efficiency does not lead to a reduction in EI. These observations highlight the need to rethink traditional design criteria for PE systems from an eco-optimization perspective.

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