Review of the Indicators for Power Electronics and Sustainability

(document for public release)

Work Group CEPPS
Convertisseurs Électronique de Puissance Plus Soutenable
Indicators Topic

cnrs GDR Groupement de recherche
SEEDS Systèmes d'énergie électrique dans leurs dimensions sociétales

https://seeds.cnrs.fr/gt-convertisseurs-electronique-de-puissance-plus-soutenables/

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Table of contents

Version tracking

- Versions :
  - 17/04/2023 – Creation of the document – H. Helbling, F. Salomez
  - 30/06/2023 – Formatting the document for public release – F. Salomez
  - 02/11/2023 – English Translation – F. Salomez

A. Identification of indicators for sustainability in power electronics (PE)

These indicators are applicable to electrical engineering, and power electronics in particular.

List of indicators

1. Gain in CO_2 eq. emissions
2. Health index of power transformer
3. Carbon Payback Period
4. Energy Payback Period
5. Reduction in GHG emissions
6. Simplified LCA on embodied energy
7. Residual Value
8. Power efficiency
9. Life Cycle Efficiency
10. Volumic Power Density
11. Mass Power Density
12. Mean Time Between Failure

the order presented here corresponds to the chronological order in which the indicators were identified

A01. Gain in CO2 eq. emissions

Saved energye after improvements ↓

gain in CO2 ⟶ $$A_{CO_2} = \Delta W^{a}_{T,savings} \cdot k_{conv}$$ ⟵ C02 rate of the energy mix comes from "European Investment Bank", *EIB Project Carbon Footprint Methodologies: Methodologies for the Assessment of Project GHG Emissions and Emission Variations*, 2020.

$$\left[\frac{tons\ CO_{2,éq}}{an}\right] = \left[\frac{MWh}{an}\right] \cdot \left[\frac{tons\ CO_{2,éq}}{MWh}\right]$$

Title	**The impact of Power transformers on the Energy Performance Indicators of the power distribution grids of industrial end-users transitioning towards environmental sustainability**
Year	2021
DOI	10.1109/MPS52805.2021.9492714
Publication Type	International Conference
Sub-field in electrical engineering	Power Grid, transformer (Textile, Aluminium, Chemical, automotive industries)
Related Inidcators and energy flux	GHG (Green House Emission)

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	
Recycling	
End of Life	

A02. Health index of power transformer

Without unity between 0 and 1

$$HI = 0{,}6 \cdot \frac{\sum_i K_i \cdot HIF_i}{\sum_i 4K_i} + 0{,}4 \cdot \frac{\sum_j K_j \cdot HIF_j}{\sum_j 4K_j}$$

- K_i, K_j : weighting factor
- HIF_i, HIF_j : health index factors (almost 20 : load history, power factor...)

Approximately 40% of the faults are due to the Load Tape Changer, GT CIGRE

Title	**An approach to power transformer asset management using health index**
Year	2009
DOI	10.1109/MEI.2009.4802595
Publication Type	Journal
Sub-field in electrical engineering	Power Transformer for the grid, with winding
Related Inidcators and energy flux	Prediction of transformer health for maintenance, replacement

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	
Recycling	
End of Life	

A03. Carbon Payback Period

$$\text{Payback period} = \frac{\text{Lifetime emissions}}{\text{Annual emission displacement}}$$

$$[An] = \frac{[gCO_{2,éq}]}{\left[\frac{gCO_{2,éq}}{An}\right]}$$

[1] R. C. Thomson, « Carbon and energy payback of variable renewable generation », The University of Edinburgh, 2014. Consulté le: 23 janvier 2023. [En ligne]. Disponible sur: https://era.ed.ac.uk/handle/1842/8875

Title	**Full life cycle assessment of two surge wave energy converters**
Year	2019
DOI	https://doi.org/10.1177/0957650919867191
Publication Type	Journal
Sub-field in electrical engineering	Energy production
Related Inidcators and energy flux	GHG (Green House Emission)

Life Cycle Phases	considered
Raw material extraction	X
Manufacturing	X
Distribution/Transport	X
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	X
Recycling	X
End of Life	X

A04. Energy Payback Period

$$\text{Payback period} = \frac{\text{Lifetime energy consumption}}{\text{Annual energy production}}$$

$$[\text{An}] = \frac{[kWh]}{\left[\frac{kWh}{An}\right]}$$

[1] R. C. Thomson, « Carbon and energy payback of variable renewable generation », The University of Edinburgh, 2014. Consulté le: 23 janvier 2023. [En ligne]. Disponible sur: https://era.ed.ac.uk/handle/1842/8875

Title	**Full life cycle assessment of two surge wave energy converters**
Year	2019
DOI	https://doi.org/10.1177/0957650919867191
Publication Type	Journal
Sub-field in electrical engineering	Energy Production
Related Inidcators and energy flux	Embodied energy

Life Cycle Phases	considered
Raw material extraction	X
Manufacturing	X
Distribution/Transport	X
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	X
Recycling	X
End of Life	X

A05. Reduction in GHG emissions

emission reduction index for subsystem k

$$ERPI^k = \sum_{i=1}^{NP} EI_i^k \cdot ERPI_i^k$$

Number of pollutants

Weighting coefficient

$$ERPI_i^k = 1 - \frac{PE_i^k}{PE_i^0}$$

emission reduction index for pollutant i

Distributed generation case

$$PE_i^k = \sum_{j=1}^{B} EG_{Aj}^k \cdot AE_{ij} + \sum_{d}^{D} EDG_d^k \cdot AE_{id}$$

Converted energy [MWh]

Generated energy [MWh]

Ref. case

$$PE_i^0 = \sum_{j=1}^{B} EG_j^0 \cdot AE_{ij}$$

Emissions value [??/MWh]

Title	**Evaluating the technical benefits of AC–DC hybrid distribution systems consisting of solid-state transformers using a multiobjective index**
Year	2019
DOI	https://doi.org/10.1016/j.segan.2019.100224
Publication Type	Journal
Sub-field in electrical engineering	Energy Production and power Grid
Related Inidcators and energy flux	GHG (greenhouse gas) emissions, with a specially constructed indicator (to be compared with a reference case).

Life Cycle Phases	**considered**
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	X
Recycling	
End of Life	

A06. Simplified LCA on the embodied energy

$$E_{ACV} = \sum M_m \cdot E_{p,m} + \int_{T_{use}} P_{fct} \cdot dt$$

Used energy during use phase

Material mass [kg]

energy cost of all transformations/processes undergone per kg of material [Wh/kg]

Title	**Eco-Dimensioning Approach for Planar Transformer in a Dual Active Bridge (DAB) Application**
Year	2021
DOI	https://doi.org/10.3390/eng2040035
Publication Type	Journal
Sub-field in electrical engineering	Power Electronics, Magnetics
Related Inidcators and energy flux	Embodied energy

Life Cycle Phases	considered
Raw material extraction	X
Manufacturing	X
Distribution/Transport	
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	
Recycling	
End of Life	X

A07. Residual Value

$$V_{res} = FP_{dev}(t) \cdot e^{\frac{-t}{MTBF(t)}} \cdot \tau_{reuse} - \sum_{reuse\ process\ p} FP_p(t)$$

Mean Time Between Failure

environmental footprint of the component/subsystem

reuse rate

environmental footprints of end-of-life/2nd life processes (quantities dependent on the study)

Title	**Design for Reuse: residual value monitoring of power electronics' components**
Year	2022
DOI	https://doi.org/10.1016/j.procir.2022.05.227
Publication Type	Journal
Sub-field in electrical engineering	Power Electronics, Magnetics
Related Inidcators and energy flux	Estimation of the residual value for a 2nd use (here generalized, in the article estimation of the remaining lifespan)

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	X
Recycling	
End of Life	

A08. Power efficiency (known as conventional)

$$\eta = \frac{P_{\text{out}}}{P_{in}} = \frac{P_{converted}}{P_{converted} + P_{losses}}$$

$$[\%] = \frac{[W]}{[W]}$$

Title	-
Year	-
DOI	-
Publication Type	-
Sub-field in electrical engineering	Electrical engineering in general
Related Inidcators and energy flux	energy

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	
Recycling	
End of Life	

A09. life cycle efficiency

$$\eta_{lca} = \frac{\int_{life} P_u(t)/\eta_e.dt}{\int_{life} P_{cons}(t)/\eta_e.dt + W_{fab+recycl\_p}} = \frac{W_{u\_p\_life}}{W_{u\_p\_life} + \left[W_{losses\_p\_life} + W_{fab+recycl\_p}\right]}$$

énergie utile convertie par le convertisseur ($W_{u\_p\_life}$)

énergie due aux pertes de conversion ($W_{losses\_p\_life}$)

énerie due au recyclage et à la fabrication ($W_{fab+recycl\_p}$)

Title	**Expériences de recherche en éco-conception dans le domaine du Génie Electrique (Research experiences in ecodesign in the field of Electrical Engineering)**
Year	2014
DOI	https://hal.science/hal-00762824/
Publication Type	Conference
Sub-field in electrical engineering	Electrical engineering in general
Related Inidcators and energy flux	Embodied energy presented as an efficiency

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	X
Distribution/Transport	
Use	X
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	
Recycling	X
End of Life	

A10. Volumic Power Density

$$\rho = \frac{P_{converted}}{Vol_{converter}}$$

$$[W.m^{-3}] = \frac{[W]}{[m^3]}$$

Title	**-**
Year	-
DOI	-
Publication Type	-
Sub-field in electrical engineering	Electrical engineering in general
Related Inidcators and energy flux	Volume of system components, indirectly mass of useful raw material (≠ of extracted)

Life Cycle Phases	considered
Raw material extraction	*indirectly*
Manufacturing	
Distribution/Transport	
Use	
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	
Recycling	
End of Life	

A11. Mass Power Density

$$\rho = \frac{P_{converted}}{m_{converter}}$$

$$[W.kg^{-1}] = \frac{[W]}{[kg]}$$

Title	**-**
Year	-
DOI	-
Publication Type	-
Sub-field in electrical engineering	Electrical engineering in general
Related Inidcators and energy flux	Mass of system components, indirectly mass of useful raw material (≠ of extracted)

Life Cycle Phases	considered
Raw material extraction	*indirectly*
Manufacturing	
Distribution/Transport	
Use	
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	
Recycling	
End of Life	

A12. Mean Time Between Failures

Mean Time Between Failures

$$MTBF = \frac{\text{Time of use} - \text{Time of failure}}{\text{Number of failure}}$$

Title	-
Year	-
DOI	-
Publication Type	-
Sub-field in electrical engineering	Lifetime estimator
Related Inidcators and energy flux	Lifetime estimator

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	indirectly
Recycling	
End of Life	indirectly

B. Identification of indicators for sustainability not directly applicable in EP

These indicators are not directly applicable in EP, and require adaptation work.

List of indicators

1. Repairability index France
2. Ease of disassembly

the order presented here corresponds to the chronological order in which the indicators were identified

B01. Repairability index France

Without unity
A score out of 10

$$ind_{rep} = \sum_c \sum_s n_{c,s/10} \cdot k_{c,s}$$

Weighting coefficient

$$n_{c,s} = \sum_{ss} n_{c,s,ss}$$

5 criteria c represented by a score out of 10 for each sub-criteria s

each sub-criterion is itself the sum of sub-sub-criteria

Critères c

C1	Documentation
C2	Disassembly access
C3	Availability of spare parts
C4	Price
C5	Device class specific

aggregate of a lot of information: availability of parts (manufacturer, distributor, repairer, etc.), number of disassembly steps, type of fixings, documentation...
=> possible bias/masking effects

Title	**Indice de réparabilité**
Year	2021
DOI	https://www.indicereparabilite.fr/grilles-de-calcul/ https://www.ecologie.gouv.fr/indice-reparabilite
Publication Type	Documents, gouvernment website
Field	Repair of consumer items (smartphones, laptops, televisions, lawn mowers, porthole washing machines, top washing machines, dishwashers, vacuum cleaners, high-pressure cleaners)
Related Inidcators and energy flux	Score for repair

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	X
Recycling	
End of Life	

autres systèmes : S. Dangal, J. Faludi, et R. Balkenende, « Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness », *Sustainability*, vol. 14, nº 14, Art. nº 14, janv. 2022, doi: .10.3390/su14148634

B02. Ease of disassembly

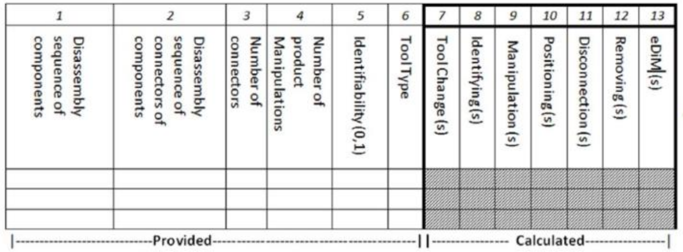
Ease of disassembly modelled in [s]

component i

ease of Disassembly Metric

$$e_{DiM} [s] = \sum_{i=1}^{i=n} (Tool\ Change_i + Identifying_i + Manipulation_i + Positioning_i + Disconnection_i + Removing_i)$$

time data provided by the database based on *Maynard operation sequence technique* (MOST)



1	2	3	4	5	6	7	8	9	10	11	12	13
Disassembly sequence of components	Disassembly sequence of connectors of components	Number of connectors	Number of product Manipulations	Identifiability (0,1)	Tool Type	Tool Change (s)	Identifying (s)	Manipulation (s)	Positioning (s)	Disconnection (s)	Removing (s)	eDiM (s)
Provided						Calculated						

worksheet

Title	**Ease of disassembly of products to support circular economy strategies**
Year	2018
DOI	10.1016/j.resconrec.2017.06.022
Publication Type	Journal
Field	Mechanical disassembly only (BDD MOST does not have data for operations on PCB (desoldering, etc.)
Related Inidcators and energy flux	Disassembly time

Life Cycle Phases	considered
Raw material extraction	
Manufacturing	
Distribution/Transport	
Use	
Preservation of functional value (Repair, Refurbishment, Reconfiguration, etc.)	X
Recycling	
End of Life	