



International Workshop on Integrated Power Packaging (IWIPP) 2025

How **Life **C**ycle **A**ssessment (**LCA**) Contributes to Sustainable Power Electronics ?**

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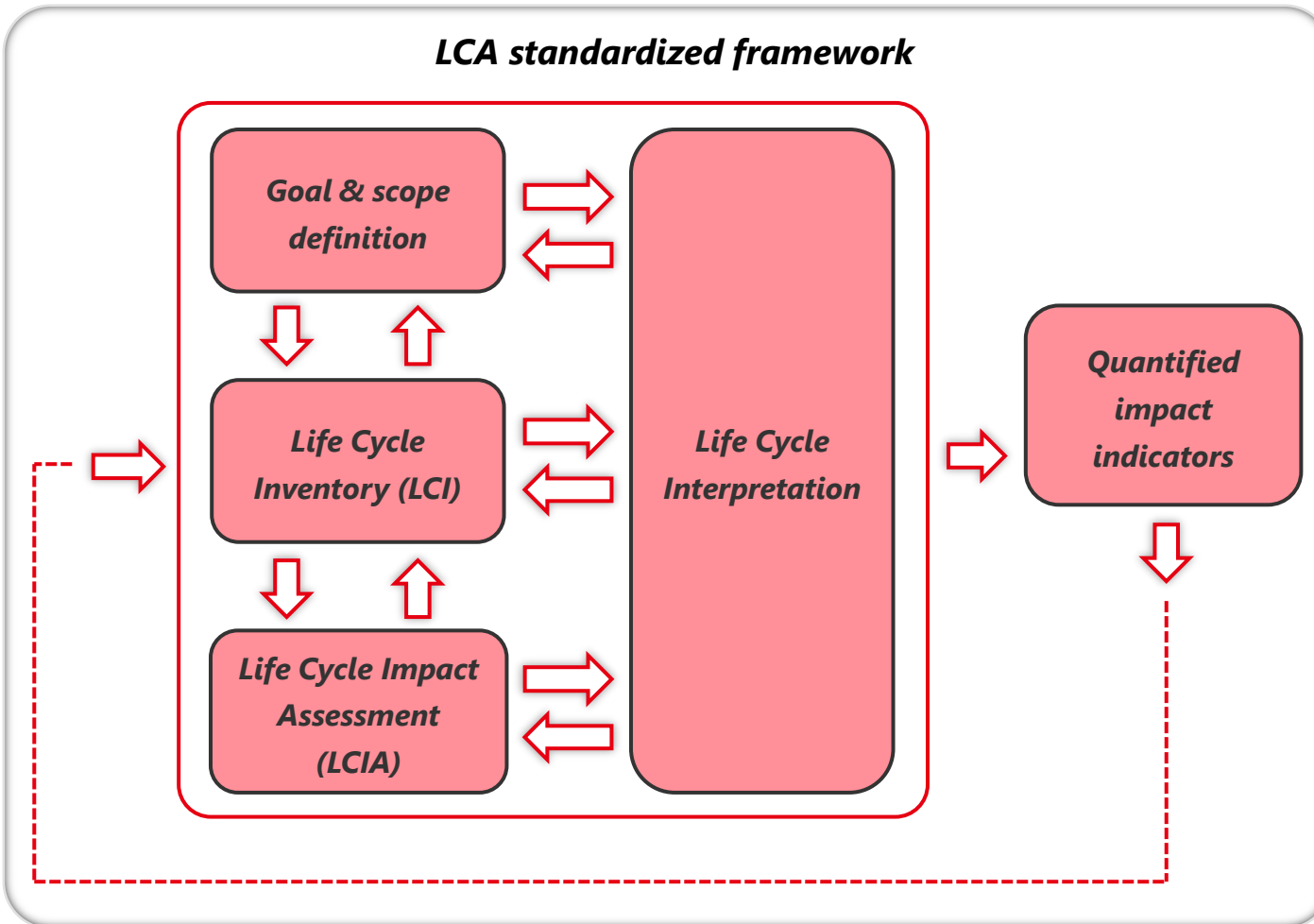
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MFR2024-ARC-1418 / MFR2024-ECD-1060

- 1. Introduction – LCA Framework & Key drivers of LCA in Power Electronics (PE)**
- 2. Some Recent Studies on LCA of PE**
- 3. LCA at Mitsubishi Electric**
- 4. Sub-parts Manufacturing Impacts Assessment**
- 5. Systems Life Cycle Impacts Assessment – PELCA software**
- 6. Take-away Messages & Perspectives**

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LCA standardized framework

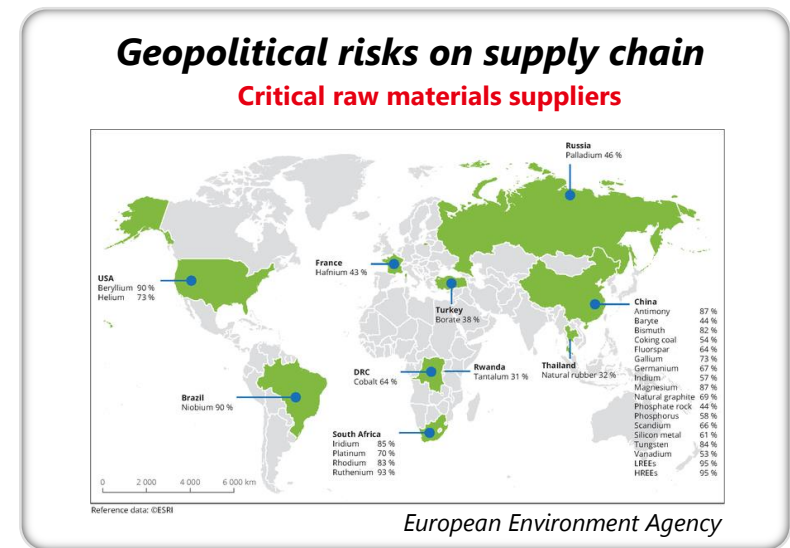
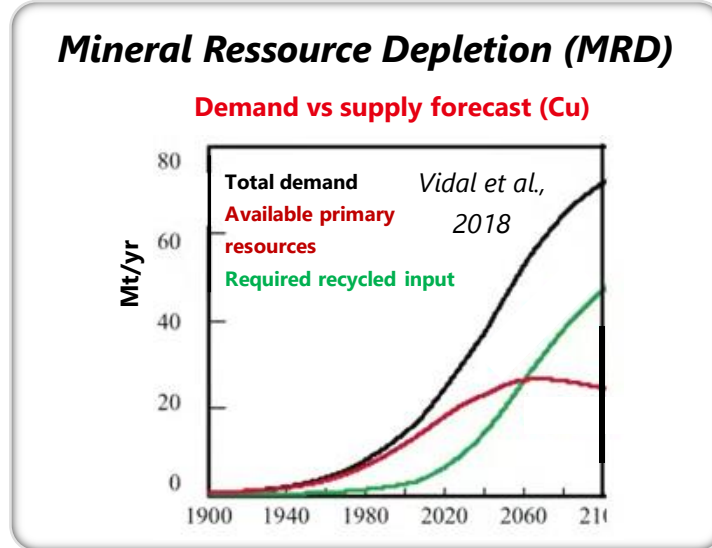
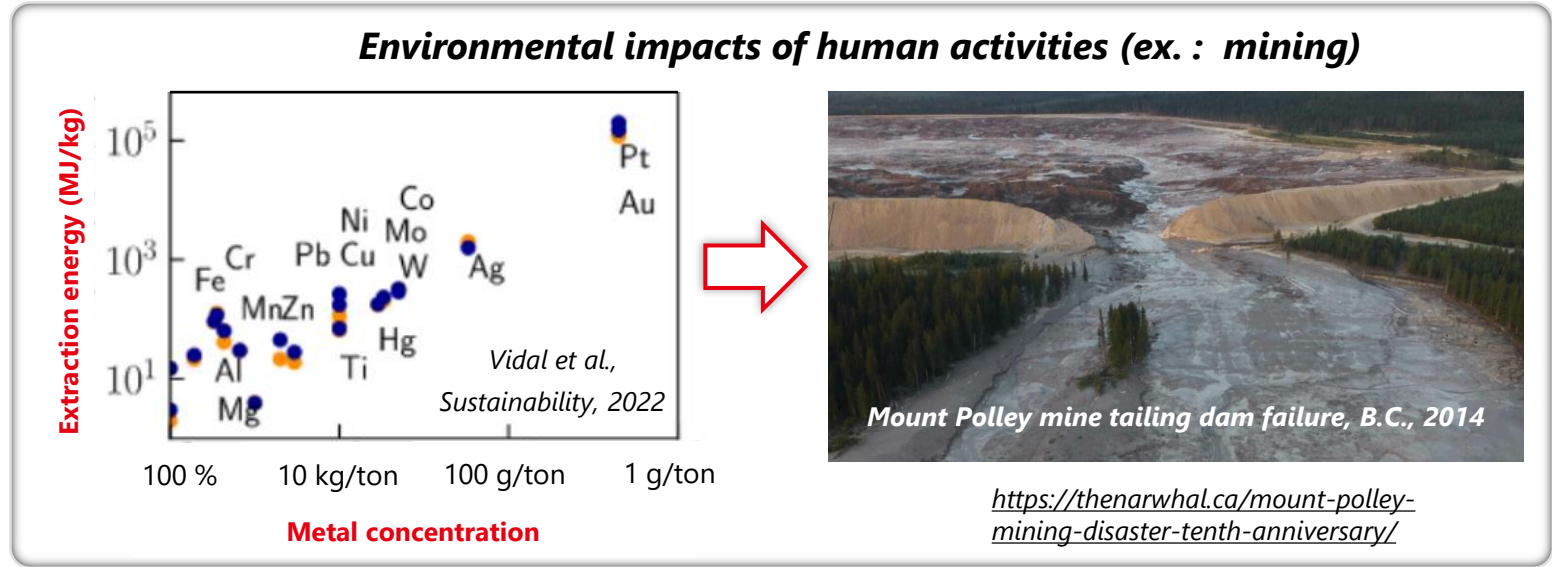
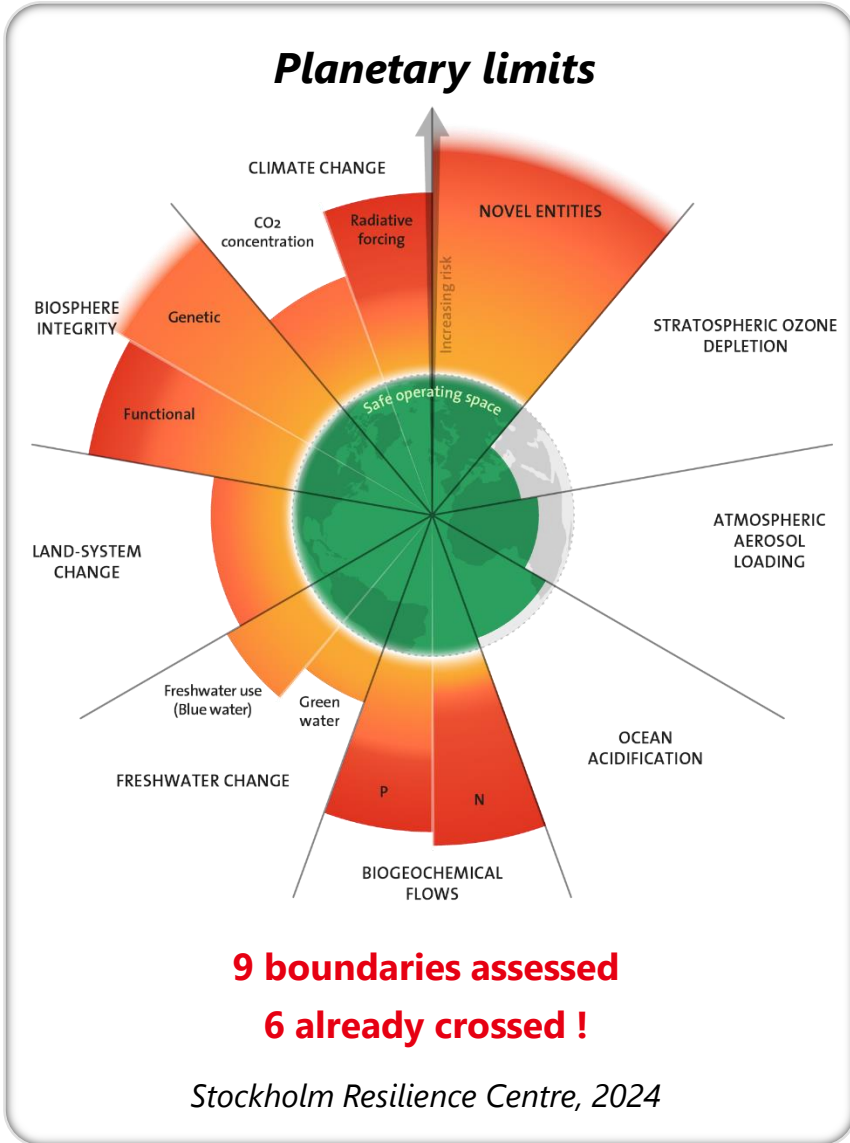


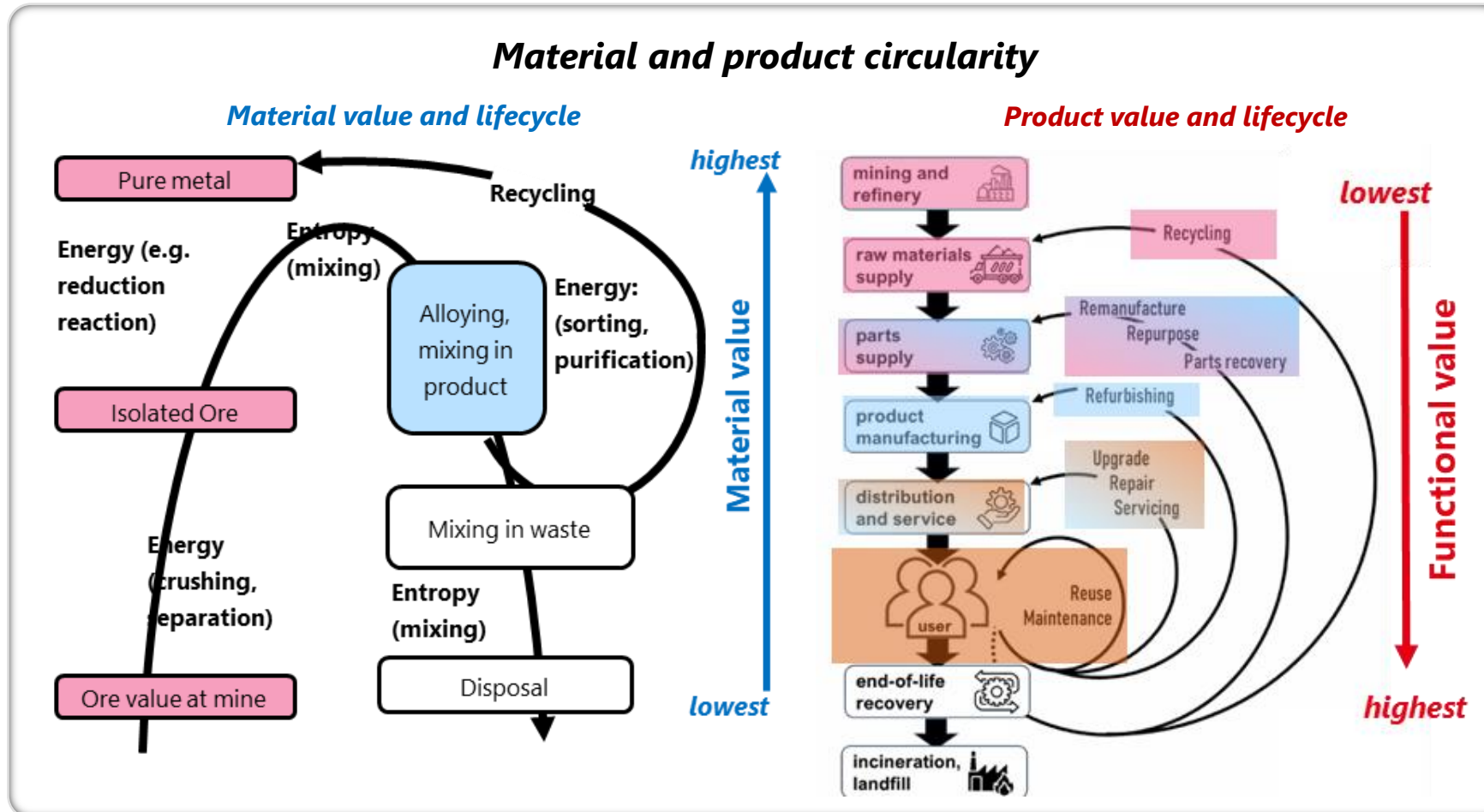
LCA ISO standards :

ISO 14040 : 2006 - Environmental management — Life cycle assessment — Principles and framework

ISO 14044 : 2006 - Environmental management — Life cycle assessment — Requirements and guidelines

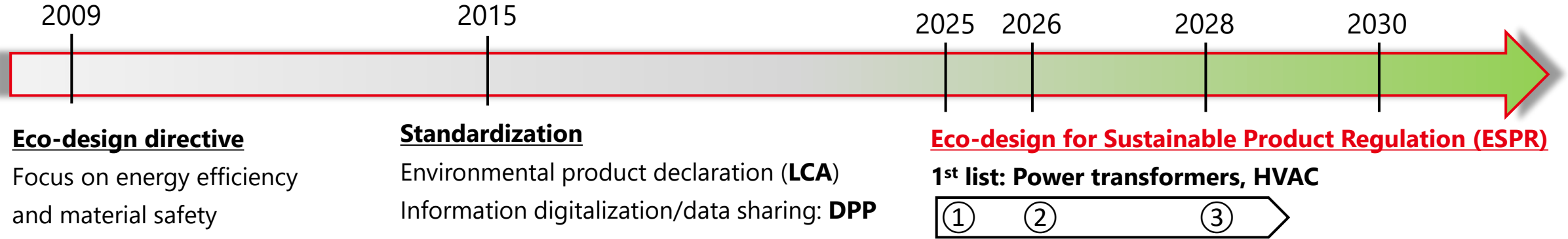
- **ISO standardized** → ISO 14040 / ISO 14044
- **Definition of Functional unit (FU)** → 3-phased DC/AC inversion of 600 A / 1200 V electrical input in Japan, in 2025
- **1\ Goal & scope definition** → Targetted hardware and system boundary definition
- **2\ Inventory** → Process inventory approach, based on teardown analysis reports, litterature sources, and internal & external expertise
- **3\ Impact assessment** → Computation of env. impacts based on established methodology & database
- **4\ Interpretation** → Contribution analysis, sensitivity & uncertainty analysis through Monte Carlo simulations
- **Iterative approach** → Feed-back loop to progressively refine model accuracy and improve its technical relevance





- Resource depletion & increase of e-waste amounts drives a **urgent need for a switch from linear to circular material life cycles** → **Material efficiency as a design criteria**
- Numerous circularity approaches → **Maintenance, Reuse, Repair, Refurbish, Remanufacture, Recycle**
- Goal: **To reduce material/energy losses along the value chain**
 - **Avoidable** → 1st law losses: energy & material efficiency along the life cycle
 - **NOT avoidable** → 2nd law (entropic) losses: dissipative processes, material cross-contamination

EU legislative timeline



- **Proactivity of EU on carbon neutrality and sovereignty targets, supported by strong standards & regulations**
- Upcoming **ESPR regulation**
- LCA as a tool of **legal compliance to access EU markets**
- LCA as a tool to **address the requests for environmental impacts data from internal / external customers**

Ecodesign for Sustainable Products Regulation
Making sustainable products the norm in the EU



Working plan adoption: 2025
Ecodesign measures adoption : 2026
Ecodesign measures enforcement :
1st list – 2028 / 2nd list - 20230

• **Si vs SiC photovoltaic (PV) inverter:**

- **Raw wafer** → SiC = x 12 higher env. impact (higher amount of energy, lower yield)
- **Power dice** → SiC = x 2,6 higher env. impact (x 8,4 smaller area)
- **PM-level / System-level** → Lower power losses with SiC → More compact design → Lower material mass → x 2,5 lower env. impact

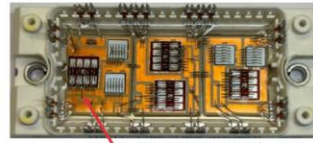
• **Si vs SiC/GaN UPS:**

- Lower manufacturing and usage impacts with WBG power devices

• **WBG technologies can enable both higher energy and material efficiency**

• **Need to consider the whole product lifecycle**

F. Musil, PCIM, 2023

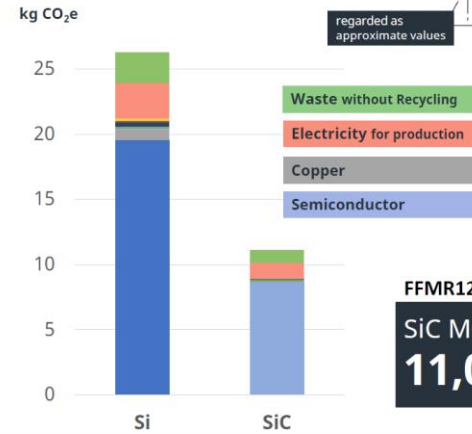


75A/1200V Si IGBT & Diode (Die area IGBT 11x11mm) (Die area Diode 7,5x7,5mm)
Weight: 179,5g

F4-75R12 KS4_B11

Si IGBT Module
26,4 kg CO2e

Manufacturing env. impact of Si vs SiC PM



regarded as approximate values

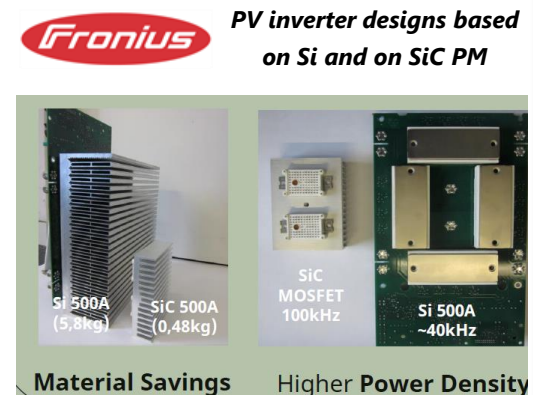


33mOhm 1200V SiC Mosfet (Die Size 3x3,5mm)
Weight: 22g

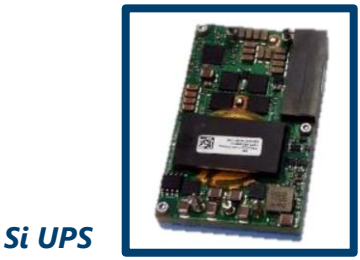
FFMR12W1M1H_B11

SiC MOSFET Module
11,0 kg CO2e

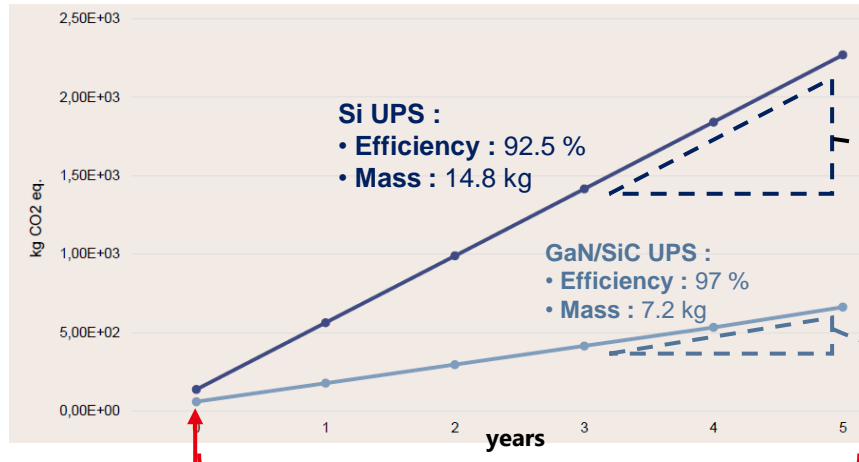
PV inverter



Material Savings **Higher Power Density**



Manufacturing and usage impact of UPS: GaN/SiC vs Si



Manufacturing impacts Usage impact

Uninterruptible Power Supply (UPS)



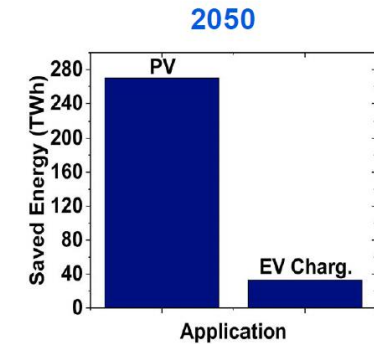
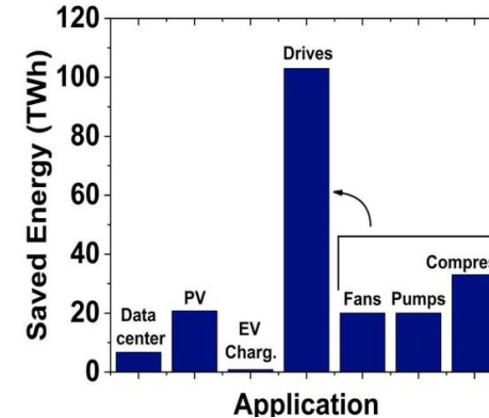
Slope α power losses

E. Chaumat, Master thesis, CEA-Leti, 2023

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- **Si vs SiC cumulative energy demand (CED) comparison at die and system-levels**
- Goal : **to assess the energy-saving potential of SiC-based systems** in the fields of motor drives, PV systems and EV charging
- **Process-based LCA to estimate impacts of Si & SiC power semiconductor manufacturing** and comparison with actual production data from **Hitachi Energy**
- **CO₂ emissions hotspots :**
 - Wafer processes
 - Yield / wafer diameter / die size
 - Electricity mix
- **SiC impact on railway traction drives:** 37 % lower lifetime cumulated energy demand (CED) vs Si
- **SiC impact on solar:** lower CO₂ emissions but at higher costs → can be mitigated by hybrid Si/SiC architecture

Energy saving estimations of SiC-based systems

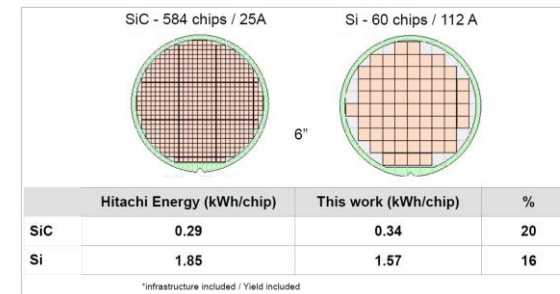


Minamisawa *et al.*, PECTA report, 2023

Wafer & die manufacturing energy budget comparison

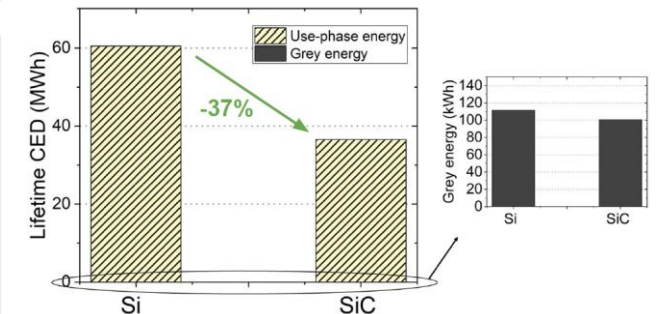
	Hitachi Energy (kWh/wafer)	This work (kWh/wafer)	%
SiC	159	191	20
Si	106	91	16

*Infrastructure included



*Infrastructure included / Yield included

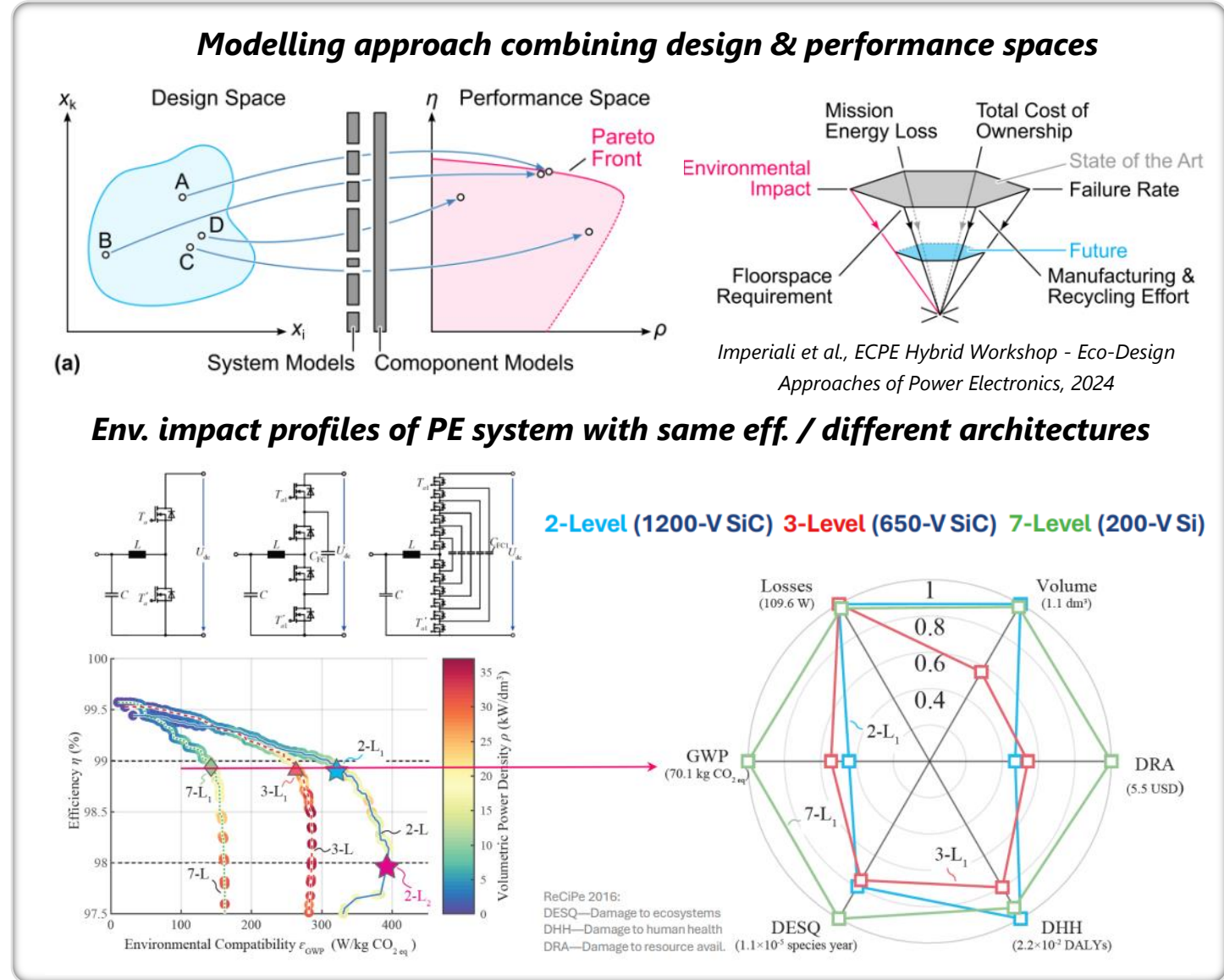
Si vs SiC lifetime CED comparison in railway applications

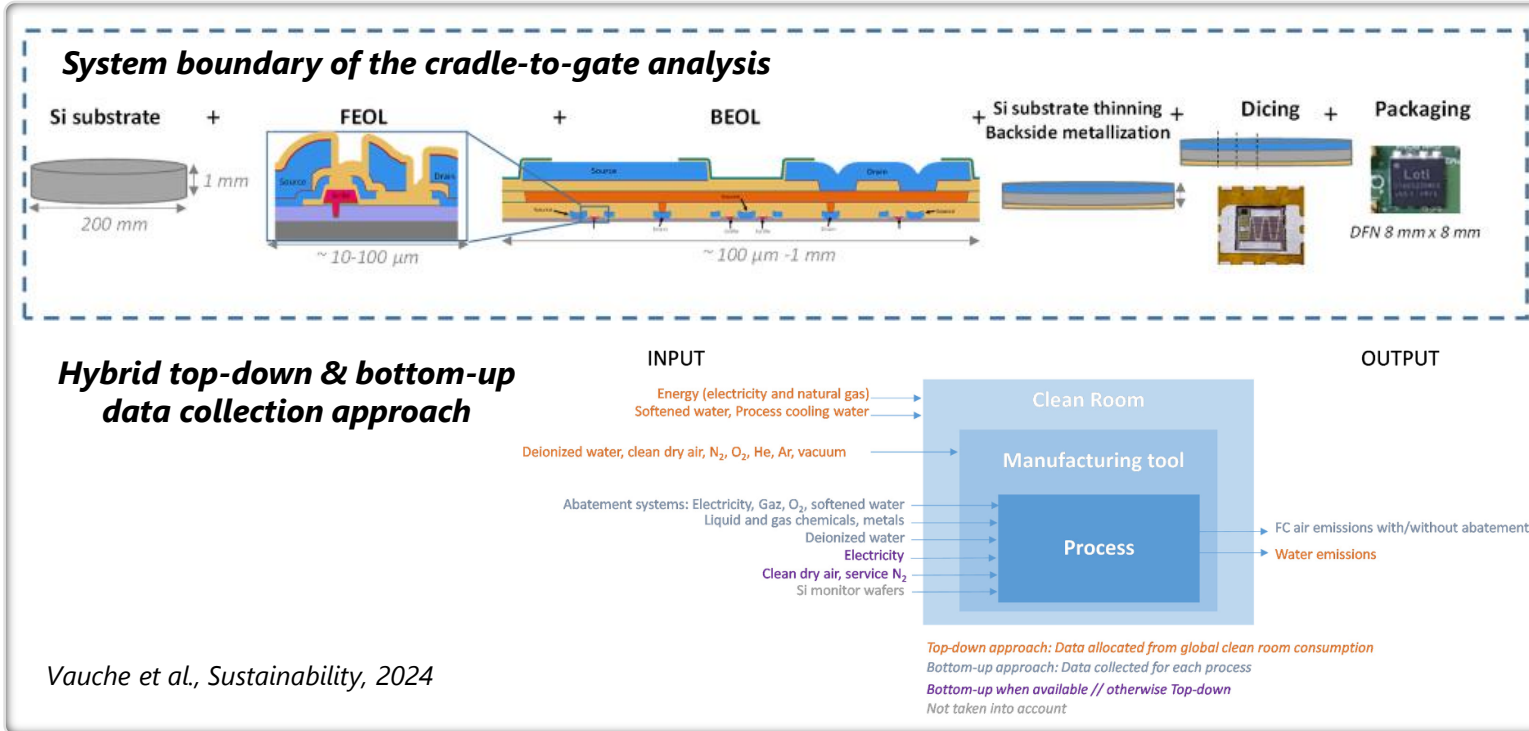


Spejo *et al.*, Power Electronic Devices & Components, 2023

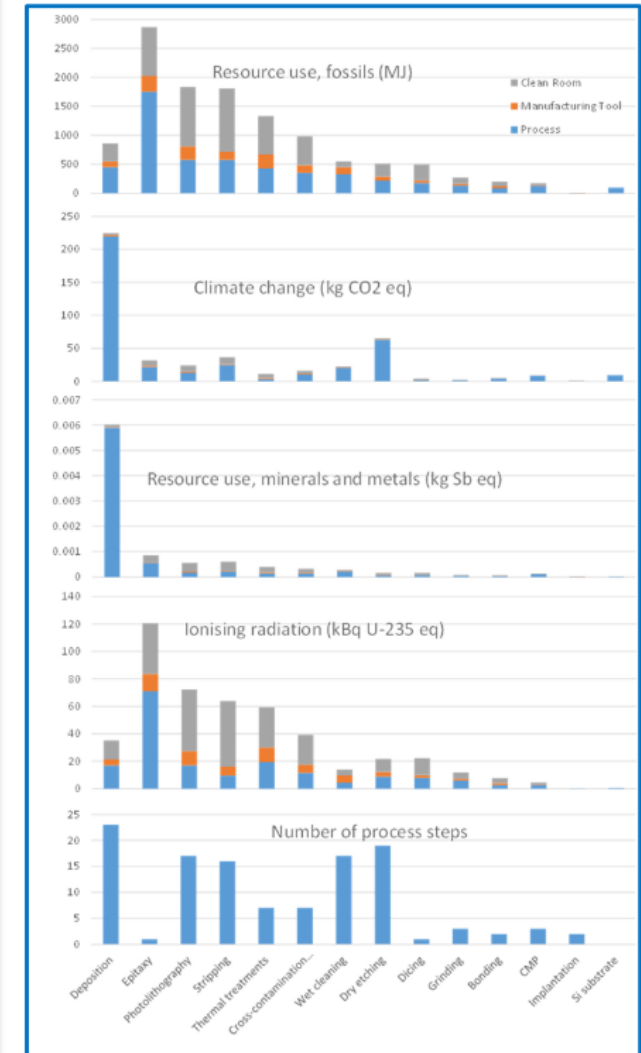


- ETH Zurich developed models of **multi-objective optimization of PE systems including an environmental compatability factor** $\rightarrow \epsilon_{GWP}$ (W/kg CO₂ eq.)
- Importance of considering the use phase / mission profile for lifecycle optimization
- PE systems with similar efficiency can exhibit very different environmental impacts !
- Proposal of a new set of performance indicators for PE systems :
 - Environmental impact [kg CO₂ eq. / kW]
 - Ressource efficiency [kg / kW]
 - Embodied energy [kWh / kW]
 - Total cost of ownership [USD / kW]
 - Power density [kW / dm³, kW / dm²]
 - Electrical yield [%]
 - Failure rate [h⁻¹]





Environmental impacts per elementary process step



- **First detailed cradle-to-gate LCA analysis of GaN-on-Si power devices** (HEMT, 200 mm diameter, R&D scale)
- **Hybrid top-down and bottom-up approach** → Proximity with clean-room process & equipment at CEA-Leti
- Strategies to mitigate environmental impacts :
 - **Gold recovery**
 - **Point-of-use gas abatement**
 - **Lower slurry consumption / slurry recovery during CMP**

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Multiscale → from subparts to system
Assessing Manufacturing & Use
Hybrid data collection (bottom-up / top-down)
Statistical → Monte Carlo simulations
Open-source & collaborative

MERCE LCA objectives

↓

1. Evaluate

↓

2. Reduce →


Technical efficiency
 → Electrical yield, power density, reliability

Repairability
 → Dismountability + diagnosis (fault identification)

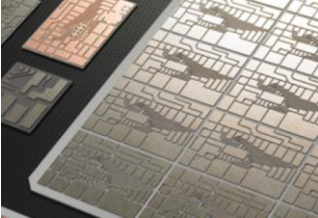
Recyclability → Materials separation capability

Power electronic subparts → **Focus on manufacturing**


Power dice (IGBT, diode, MOSFET)



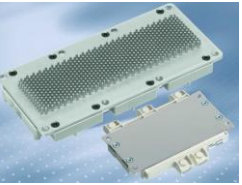
Ceramic substrate




Power modules




Baseplate




PCBs



Busbars




DC-link capacitor




Power electronic systems
 → **Focus on manufacturing and use**


HVDC substations

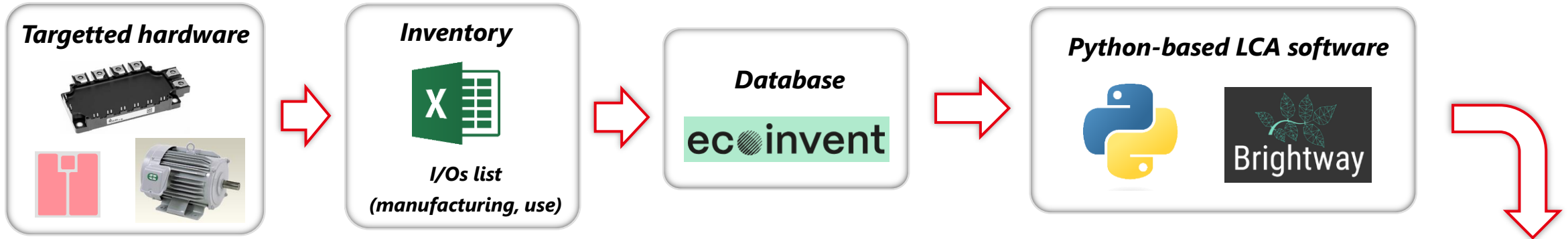


Electrical motors (PMSM)





General Purpose Inverters (GPIs)








Product Environmental Footprint (PEF) method - 16 impacts assessed


Not only GWP !







Climate change



Water use



Land use



Acidification

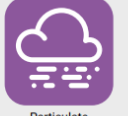

Ozone depletion



Human toxicity, non-cancer



Eutrophication marine



Ecotoxicity freshwater

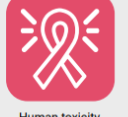

Eutrophication, terrestrial



Particulate matter

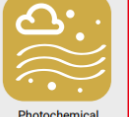

Resource use, mineral and metals

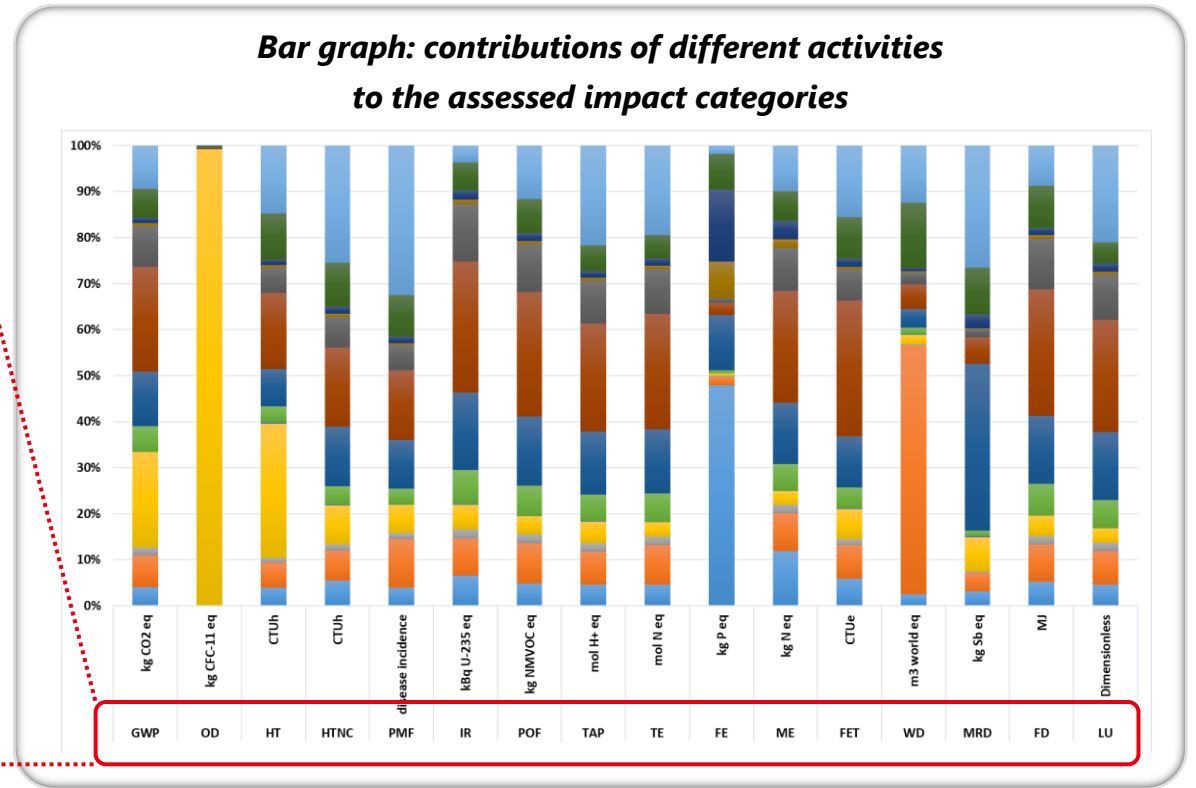

Resource use, fossils


Eutrophication, freshwater


Human toxicity, cancer


Ionising radiation, human health


Photochemical ozone formation, human health



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3-phased DC/AC inverter power module – INFINEON HybridPack Drive

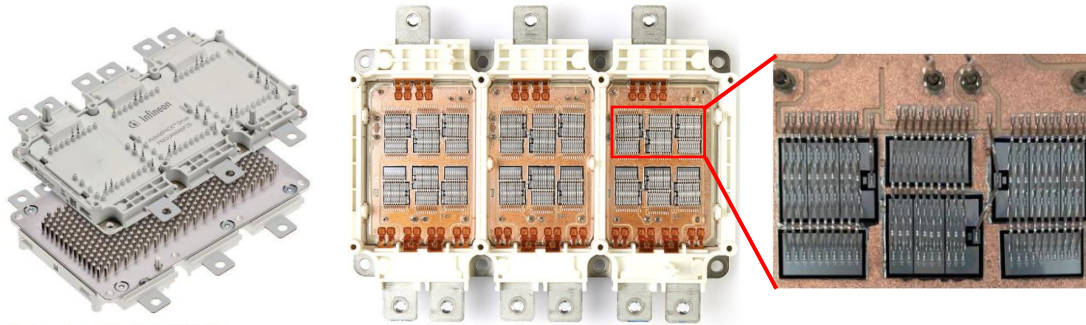
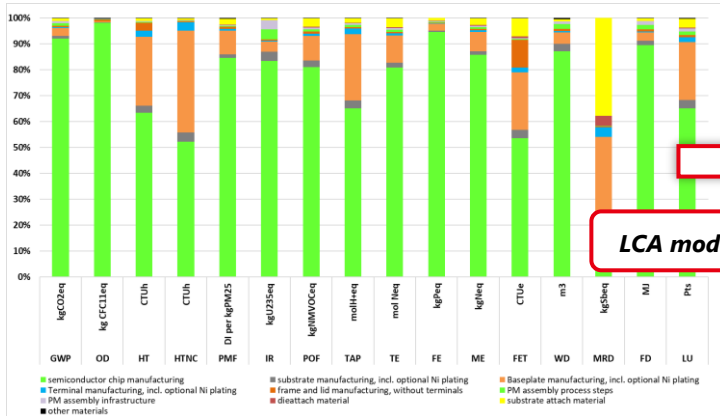


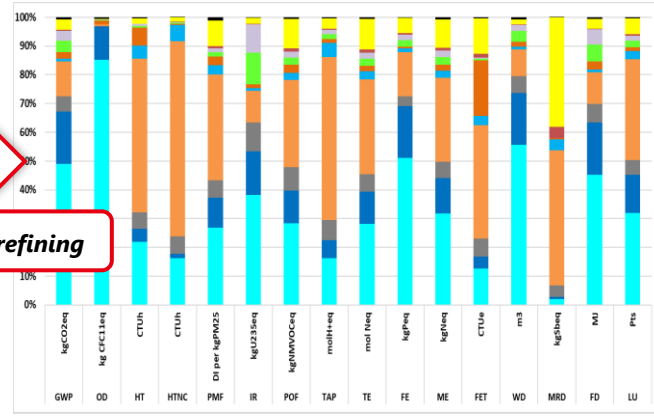
Fig.1. Overview of HybridPACK™ Drive

- Generic IC model from database (ecoinvent) → **Overestimation of all environmental impacts** due to dataset unrepresentativeness in terms of number of process steps and photomask levels
- Power module LCA with custom power semiconductor models for Si IGBT and Si diode manufacturing → **More representative datasets and higher level of confidence in the obtained LCA results**
- Similar model refinement approach is carried out on other power module subparts → **Baseplate, substrates, brazing alloys, internal & external encapsulant**

1st round (data quality limitations)

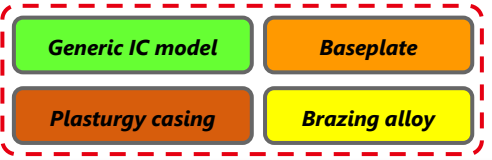
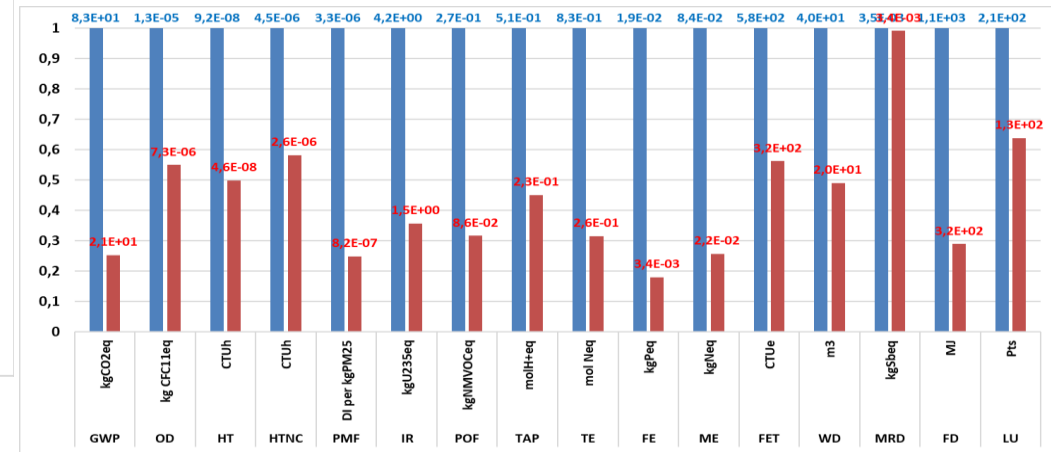


2nd round (custom semiconductor models)



1st round analysis (data quality limitations) = 100%

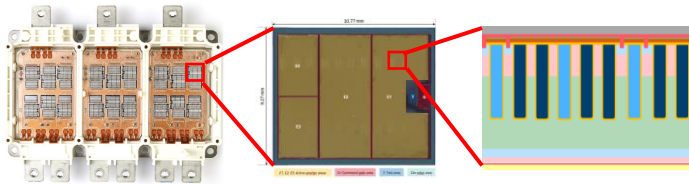
2nd round analysis (custom semiconductor models)



Identified hotspots



Trench Si power IGBT → Process breakdown analysis



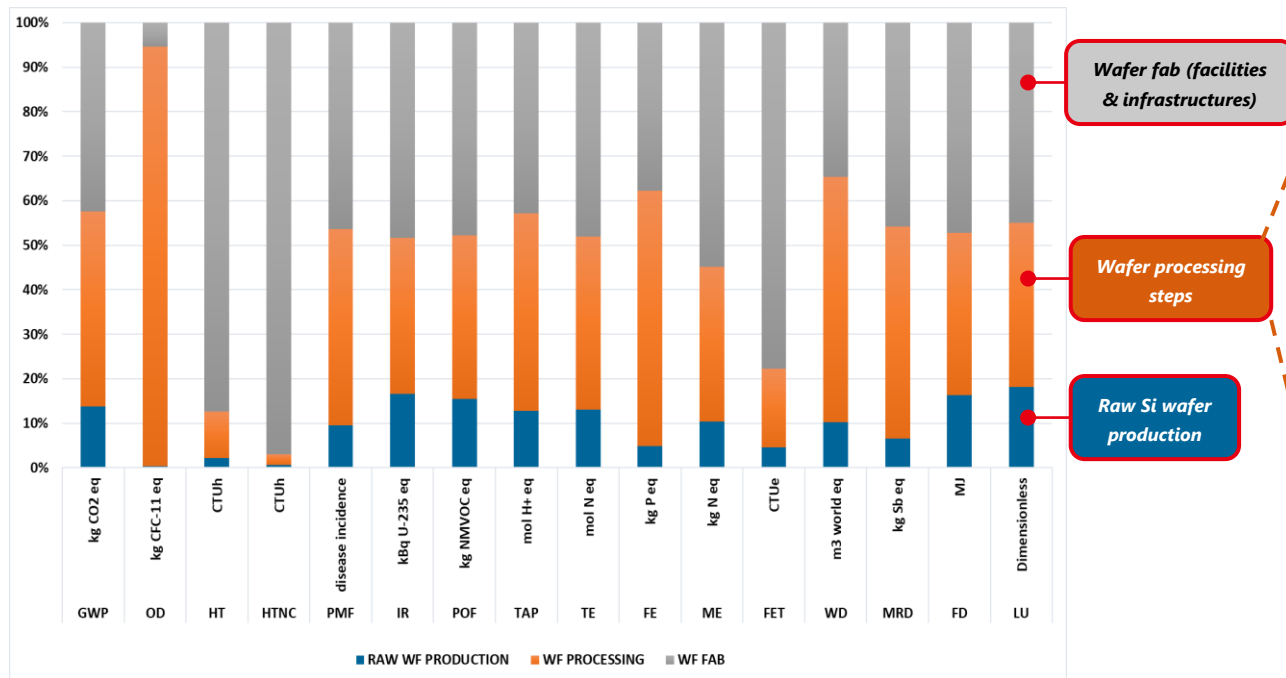
3 modelling levels :

- Wafer fab
- Elementary process
- Raw wafer production

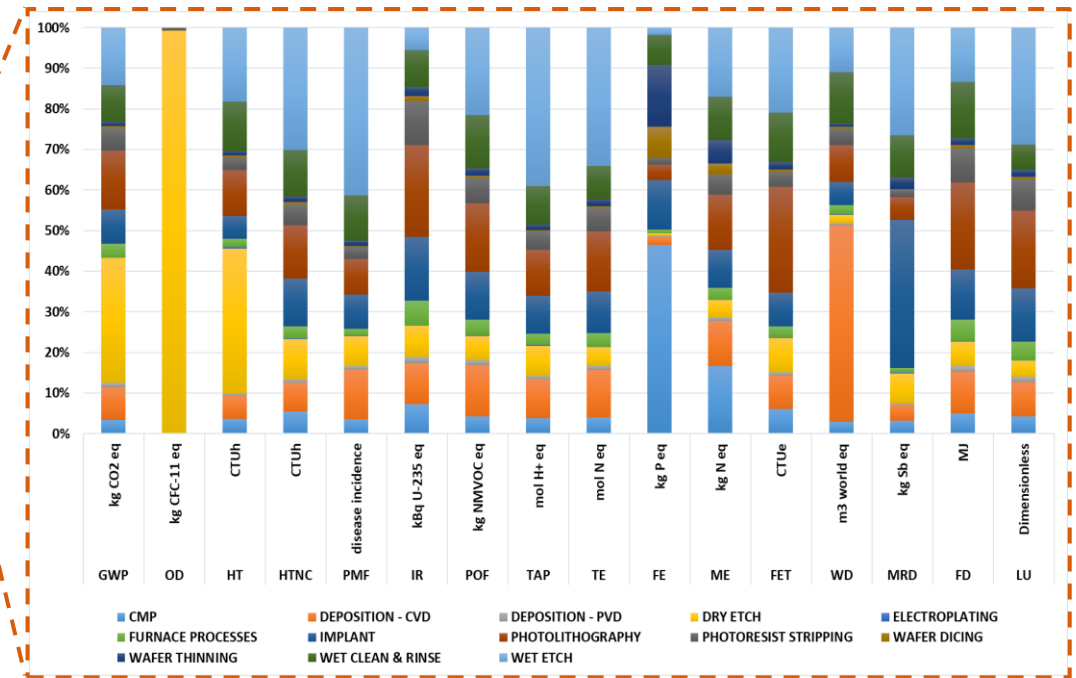
Identification of the **hotspots of the semiconductor manufacturing process** and specific **impacts reduction targets**

Major impact of wafer fab
→ Key importance of fab location and associated electricity mix

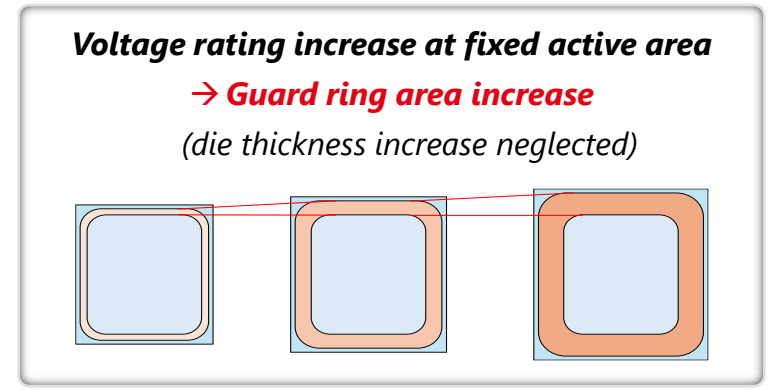
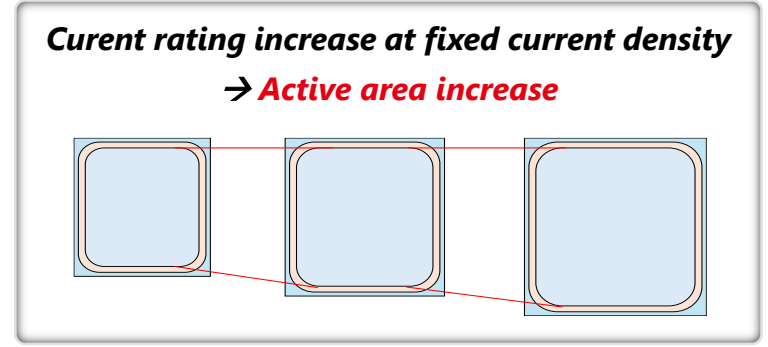
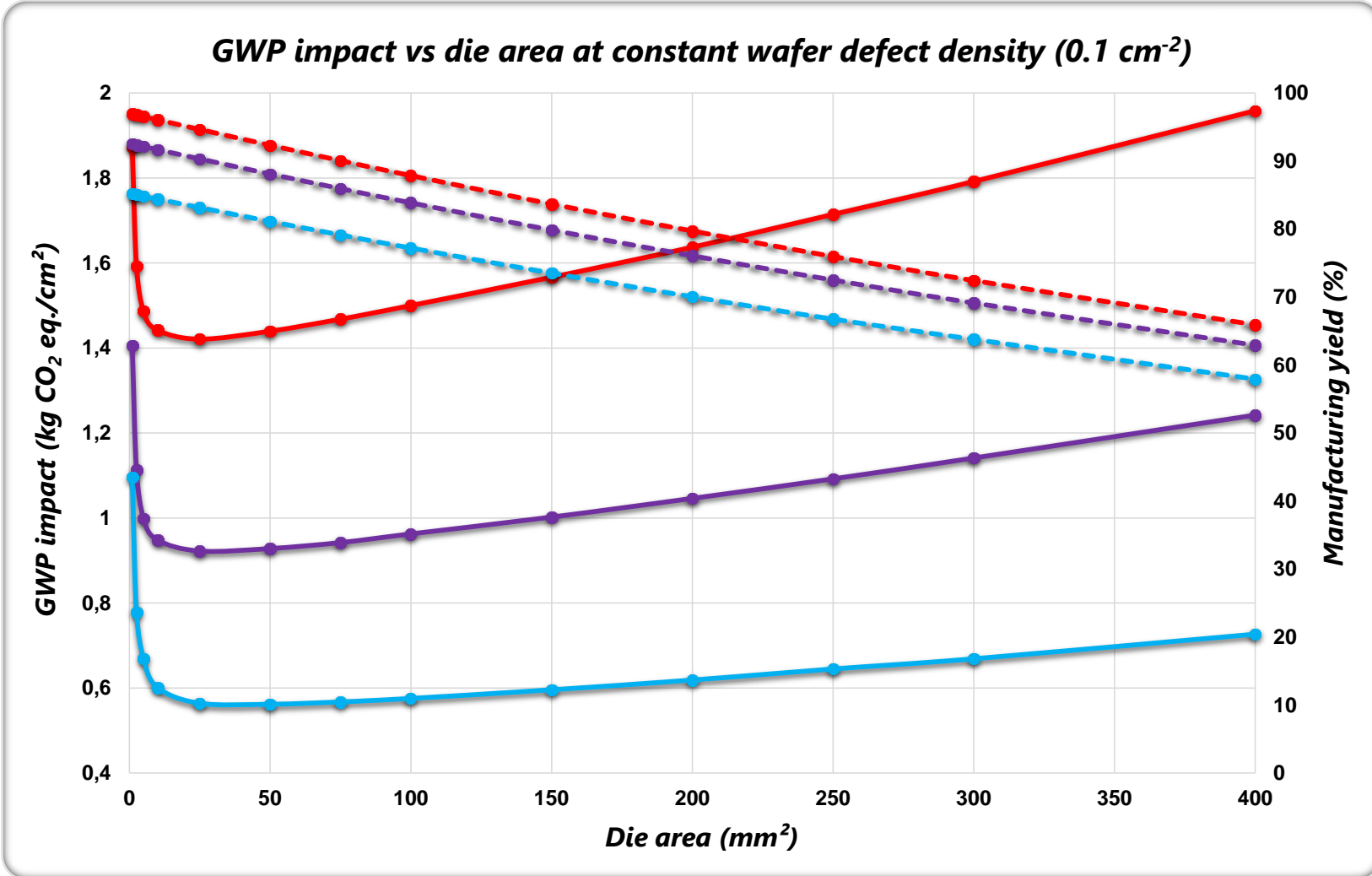
Impact share : raw Si wafer, wafer processing steps, and cleanroom infrastructures



Impact share : wafer processing steps

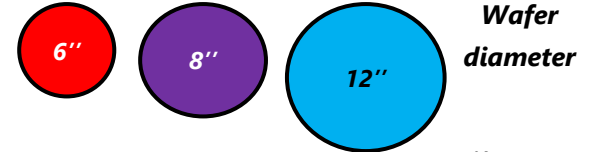


Calculation hypotheses: Wafer dia. : 200 mm, defect density : 0,1 cm⁻², fab ISO class : 4, fab location & associated electricity mix : Austria (AT), yearly wafer surface production : 36,500 m² (≈130 kwf / month)



Ability to estimate env. impacts based on die voltage / current rating & manufacturing hypotheses

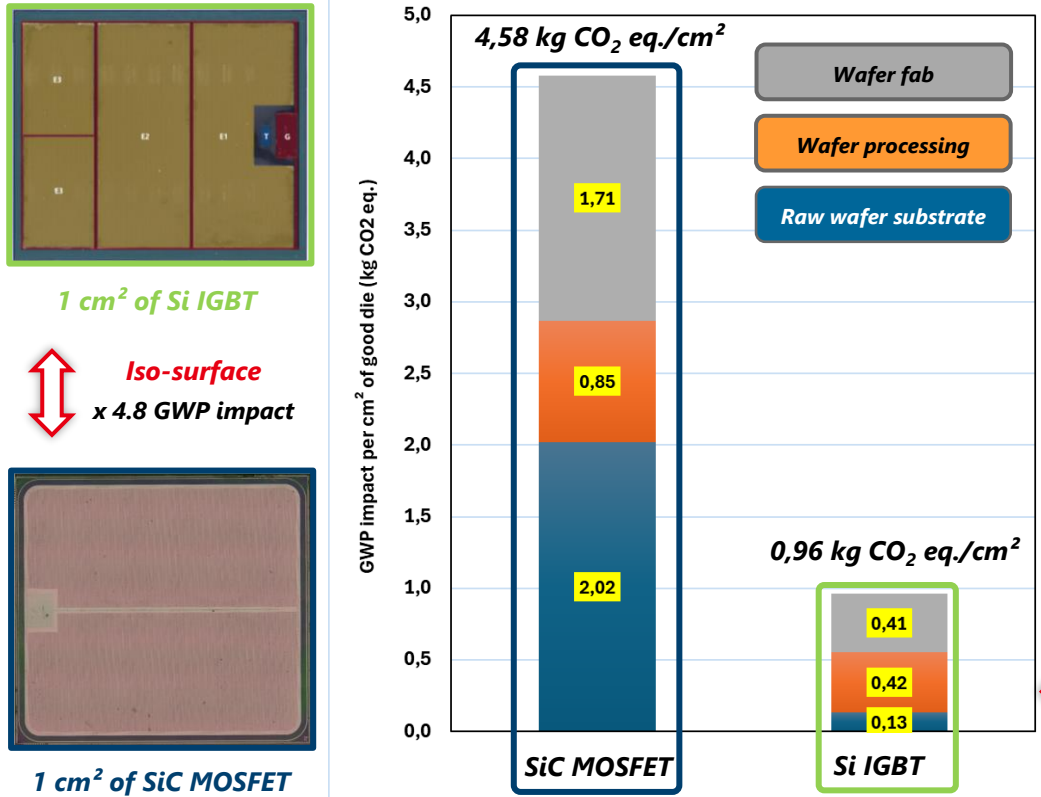
Calculation hypotheses: Die size after dicing : [1 – 400] mm², wafer defect density: 0,1 cm⁻², fab ISO class: 4, fab location: Europe (RER), yearly wafer surface production: 36,500 m²



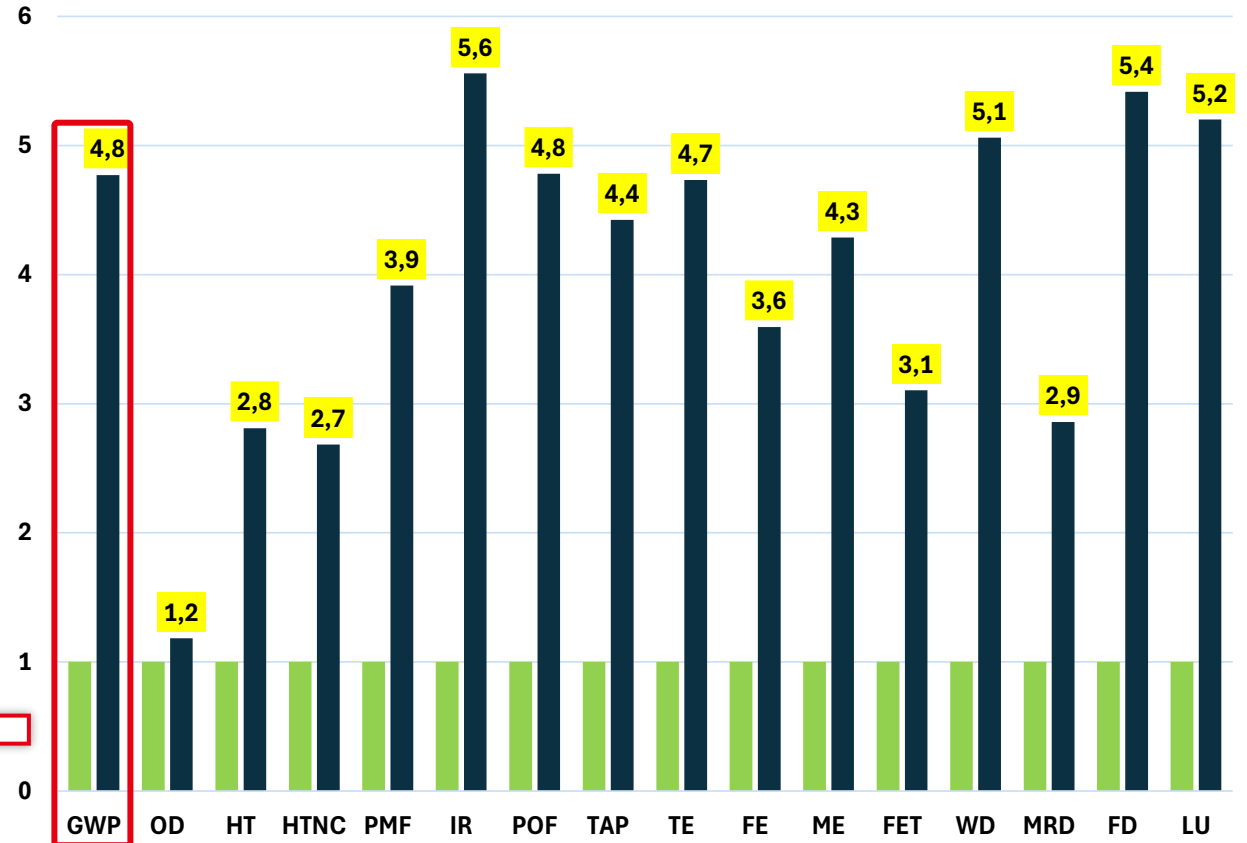
Non-confidential

At fixed die area (iso surface)

Die-level GWP impact comparison at fixed die area (1 cm²)



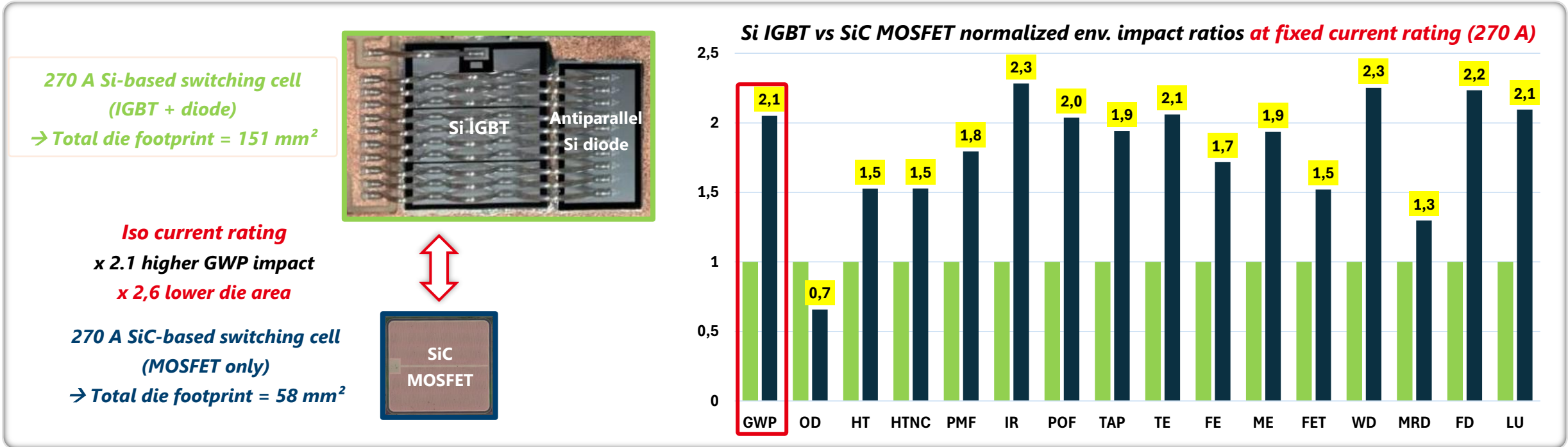
Si IGBT vs SiC MOSFET normalized env. impact ratios at fixed die area (1 cm²)



Calculation hypotheses for Si IGBT: Wafer diameter : 200 mm, wafer defect density: 0,1 cm⁻², fab ISO class: 4, fab location: Europe (RER), yearly wafer surface production: 36,500 m² (≈ 130 kwf/month)

Calculation hypotheses for SiC MOSFET: Wafer diameter : 150 mm, wafer defect density: 0,75 cm⁻², fab ISO class: 4, fab location: Europe (RER), yearly wafer surface production: 3,000 m² (≈ 30 kwf/month)

At fixed current rating (iso function)

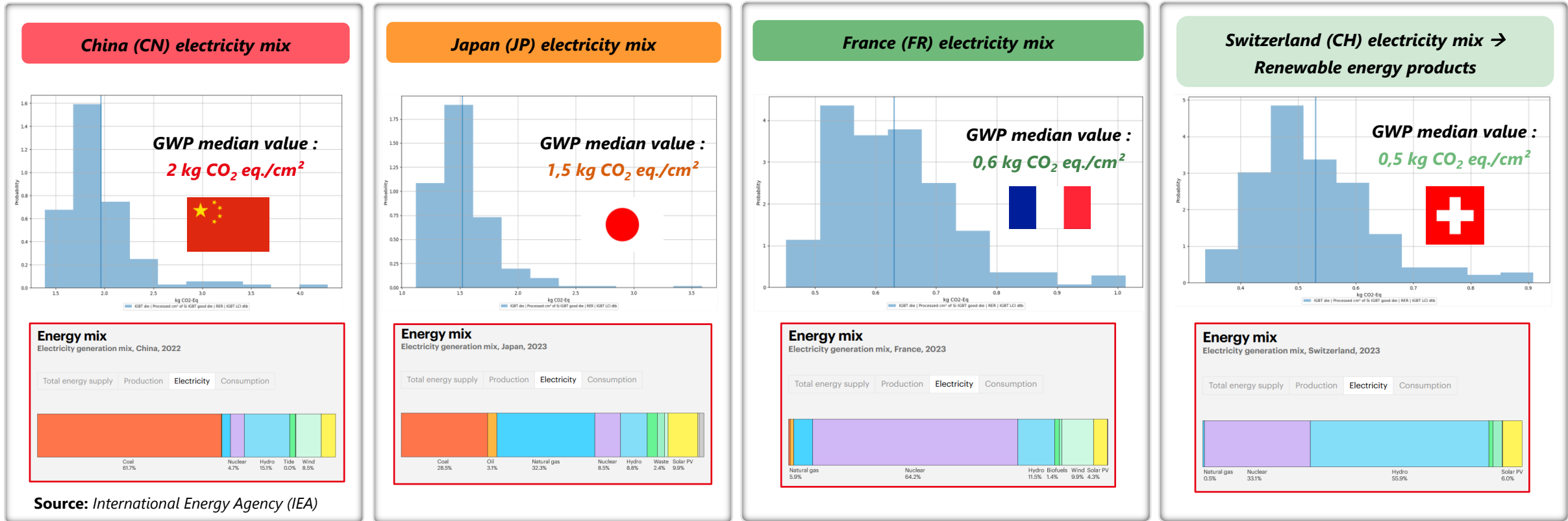


Switching cell	Si-based		SiC-based
Device	Si IGBT	Si diode	SiC MOSFET
Current caliber	270 A		270 A
Die area	99,8 mm ²	51,2 mm ²	58 mm ²
Surfacic curr. density	2,8 A/mm ²	5,3 A/mm ²	4,65 A/mm ²
Surfacic GWP	0,96 kg CO ₂ eq./cm ²	0,66 kg CO ₂ eq./cm ²	4,58 kg/cm ²
Die GWP	0,96 kg CO ₂ eq.	0,34 kg CO ₂ eq.	2,65 kg CO ₂ eq.
Switching cell area	151 mm ²		58 mm ²
Switching cell GWP	1,3 kg CO ₂ eq.		2,66 kg CO ₂ eq.
Amp./GWP metric	207,7 A/kg CO ₂ eq.		102 A/kg CO ₂ eq.

Calculation hypotheses for Si IGBT: Wafer diameter : 200 mm, wafer defect density: 0,1 cm⁻², fab ISO class: 4, fab location: Europe (RER), yearly wafer surface production: 36,500 m² (≈ 130 kwh/month)

Calculation hypotheses for SiC MOSFET: Wafer diameter : 150 mm, wafer defect density: 0,75 cm⁻², fab ISO class: 4, fab location: Europe (RER), yearly wafer surface production: 3,000 m² (≈ 30 kwh/month)

- **At iso die surface → SiC MOSFET has 4,8 higher environmental impacts wrt Si IGBT**
- **At iso current rating → SiC-based switching cell has 2.1 x higher env. impacts wrt Si-based but 2.6 x lower die area footprint**
- **Higher environmental impacts of SiC power devices must be considered along with system shrinkage**
→ Power module size, cooling system, filtering elements



- **Monte-Carlo simulations (250 trials) of the Global Warming Potential (GWP) impact of the IGBT wafer manufacturing process based on different fab locations & associated electricity mixes** → Major impact on the ecological costs of the power die fabrication process
- Monte Carlo → **Switch from a deterministic LCA approach, weakened by the scarcity of relevant data points, to a probabilistic LCA approach** → Increases the level of confidence in the results

Wafer fab location	GWP energy conversion factor (ECF) (kg CO ₂ eq. / kWh)
China (CN)	0,953
Japan (JP)	0,668
France (FR)	0,077
Switzerland (CH)	0,031

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Evolutive, collaborative open-source research software for Power Electronics LCA

Integrate **Manufacturing and Use** phase of PE systems

Based on **Replacement Units (RUs)**, i.e. modularity level

Provide **statistical results** through **Monte Carlo simulations**

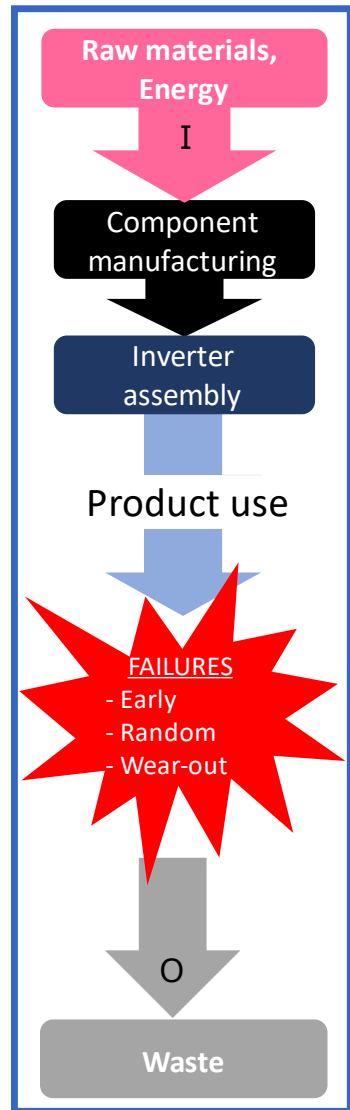
PELCA features:

- **Reliability**
→ Weibull fault parameters
- **Curative maintenance**
→ Based on faults & diagnosis
- **Preventive maintenance**
→ Based on schedule

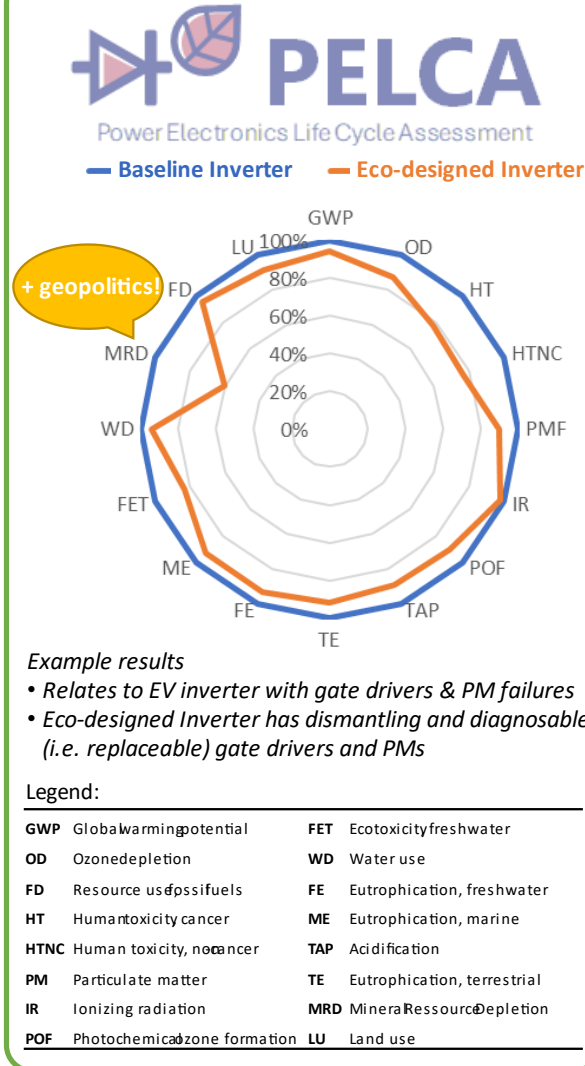
PELCA can be used to assess :

- **Environmental impacts**
- **Economic impacts**

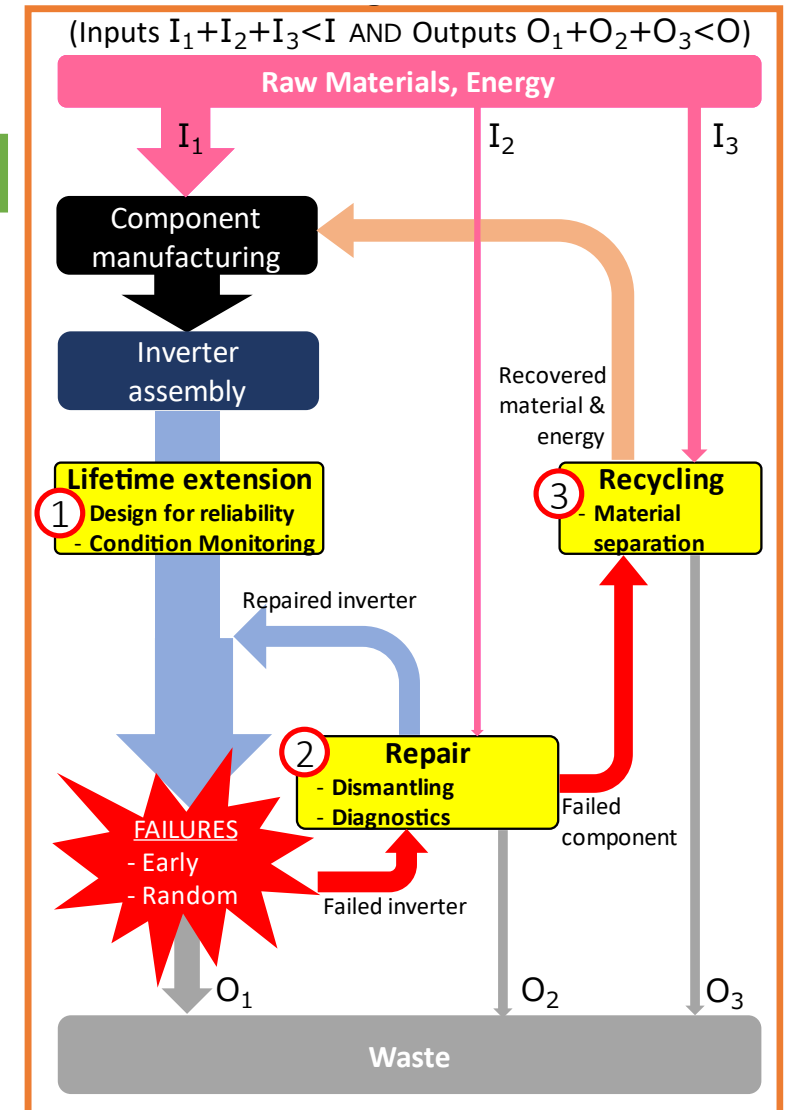
Baseline Inverter



EVALUATION



Eco-designed Inverter



Excel Input



Inventory

Manuf. + Use

Fault parameters
(Weibull)

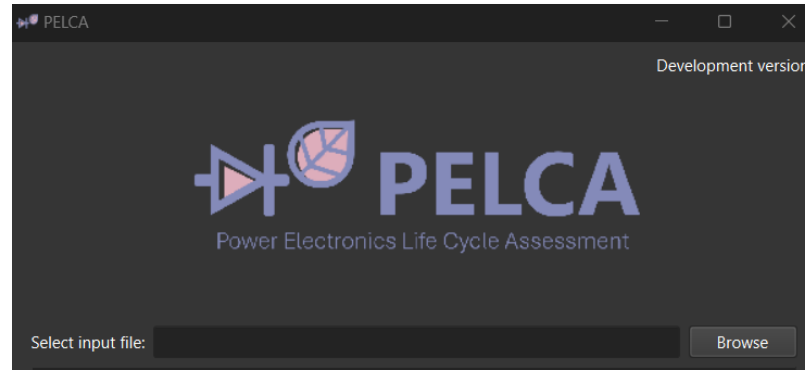
Curative Maint.
(diagnosis)

Preventive Maint.
(schedule)

Economic impact
(cost / price)

PELCA software architecture

Graphical user interface



Python-based



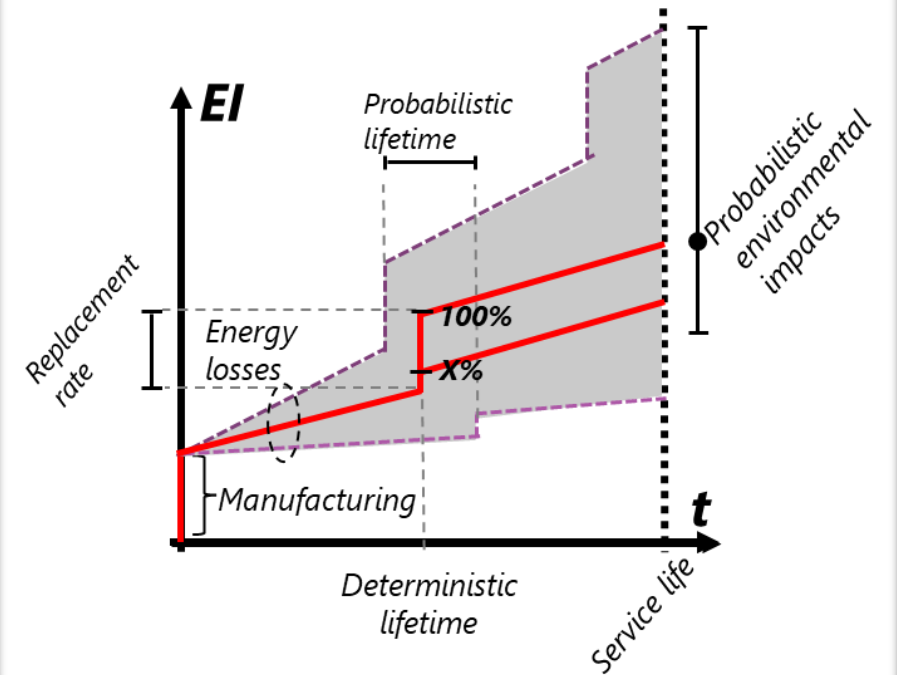
Database

ecoinvent

LCA library



Output example (staircase curve)



• Software installation:

- GitHub repository → <https://github.com/merce-fra/PELCA>
- < 1h to install and run example



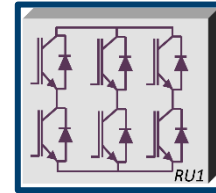
New Release now available !
PELCA v1.3.0

'Staircase' input information

Number of Replac. Unit (RU)	2
Service life (year)	30
Annual usage time (hours/year)	666
Time step (step/year)	1
Early failure	True
Random failure	True
Wearout failure	True
Preventive Maintenance	False
Monte Carlo (number of iteration)	1000
Plot specific env. impact	16

'Curative maintenance' input information → Replacement matrix

'Dummy' inverter
→ No diagnosis

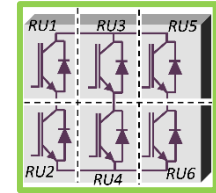


	RU1	RU2
Fault RU1	100 %	100 %
Fault RU2	100 %	100 %



100 % in all boxes :
 If fault $RU_1 = 100 \%$ probability to replace $(RU_1 + RU_2)$
 If fault $RU_2 = 100 \%$ probability to replace $(RU_1 + RU_2)$

'Smart' inverter →
 Fault identification & selective replacement



	RU1	RU2
Fault RU1	100 %	0 %
Fault RU2	0 %	100 %

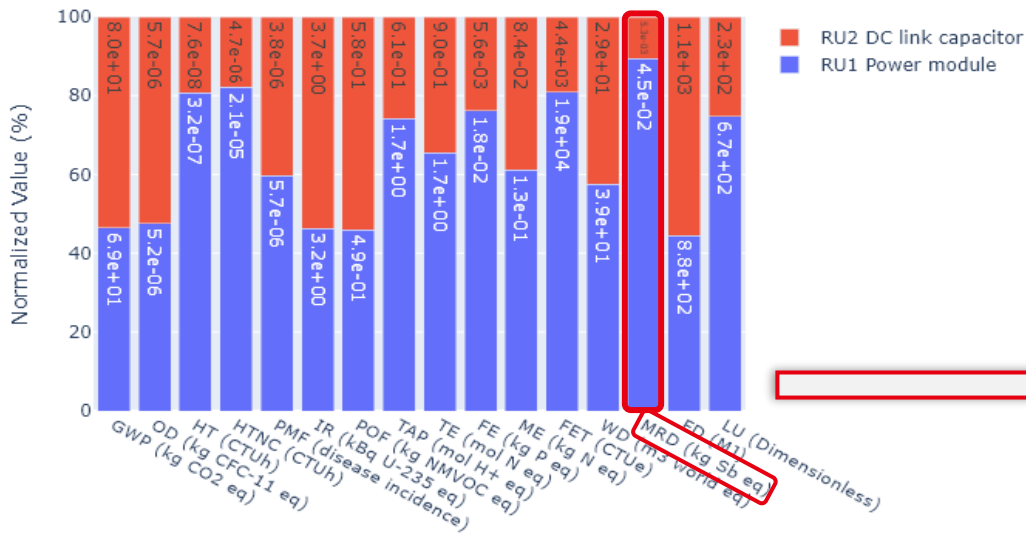


100 % in all boxes :
 If fault $RU_1 = 100 \%$ probability to replace RU_1 only
 If fault $RU_2 = 100 \%$ probability to replace RU_2 only

'Fault parameters' & 'Preventive maintenance' input information → Weibull fault parameters (σ, β) + Preventive maintenance schedule

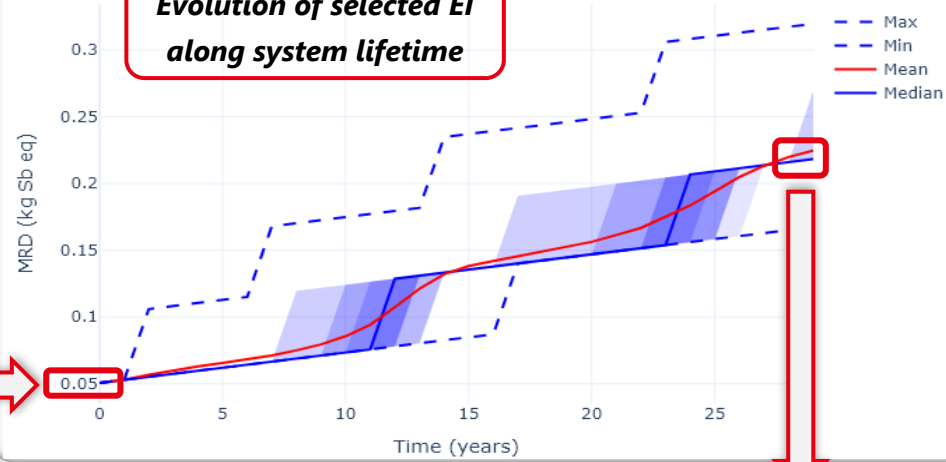
	Early failure (sigma, year)	Early failure (beta)	Random failure (sigma, year)	Random failure (beta)	Wear-out failure (sigma, year)	Wear-out failure (beta)	Prev. Maintenance (year)
RU1	1000	0,6	3000	1	40	8	7
RU2	1000	0,6	3000	1	12	8	5

Contributions of RUs to manufacturing impacts



Selected EI: MRD

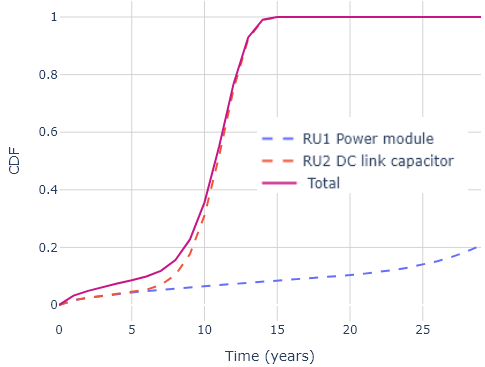
Evolution of selected EI along system lifetime



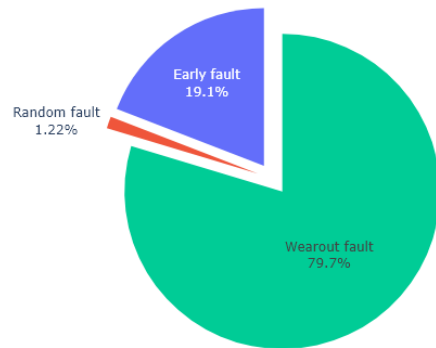
Contributions of the different life phases to env. impacts



Cumulative distribution function



Distribution of defects



PE systems → Major impact of use

Based on a given utilization rate (mission profile), env. impact must be seen as a complementary system performance indicator, to be optimized by designing systems in a 'fit-for-usage' spirit

'Cost / Price' input information

	RU raw cost/price (€)	RU assembly cost/price (€)	RU disassembly cost/price (€)	kWh cost/price (€)
Power module	400	300	300	0,25
DC-link capacitor	800	200	200	0



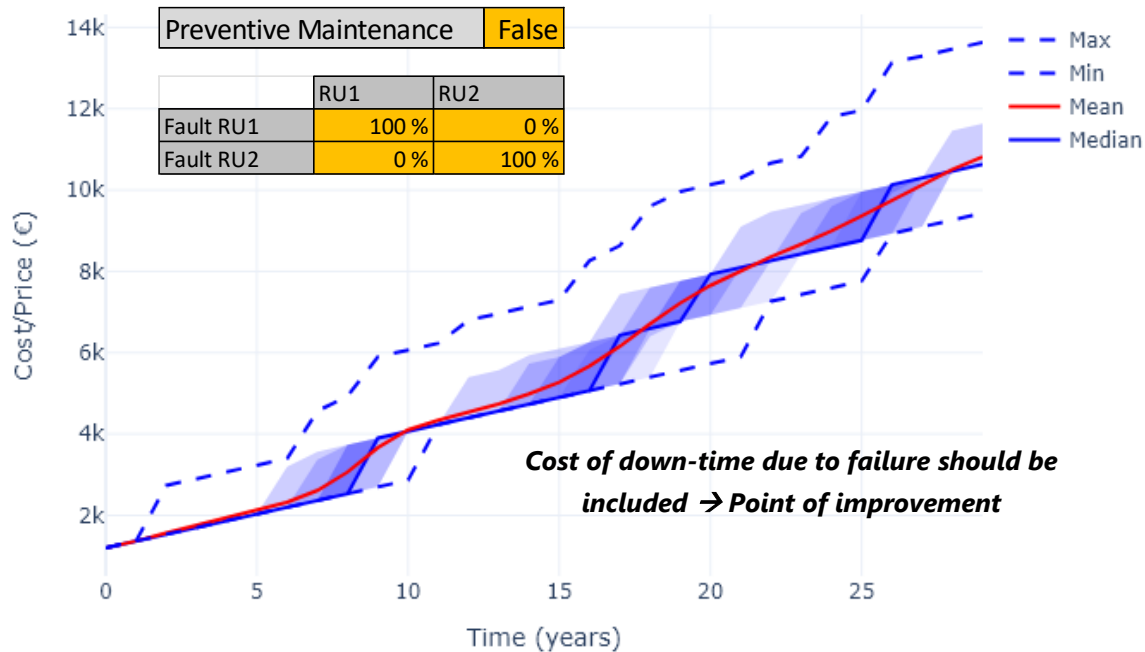
Cost of preventive maintenance:

$$Cost_{RU_i} = Cost(RU_{i_{RAW}} + RU_{i_{ASS}} + RU_{i_{DIS}})$$

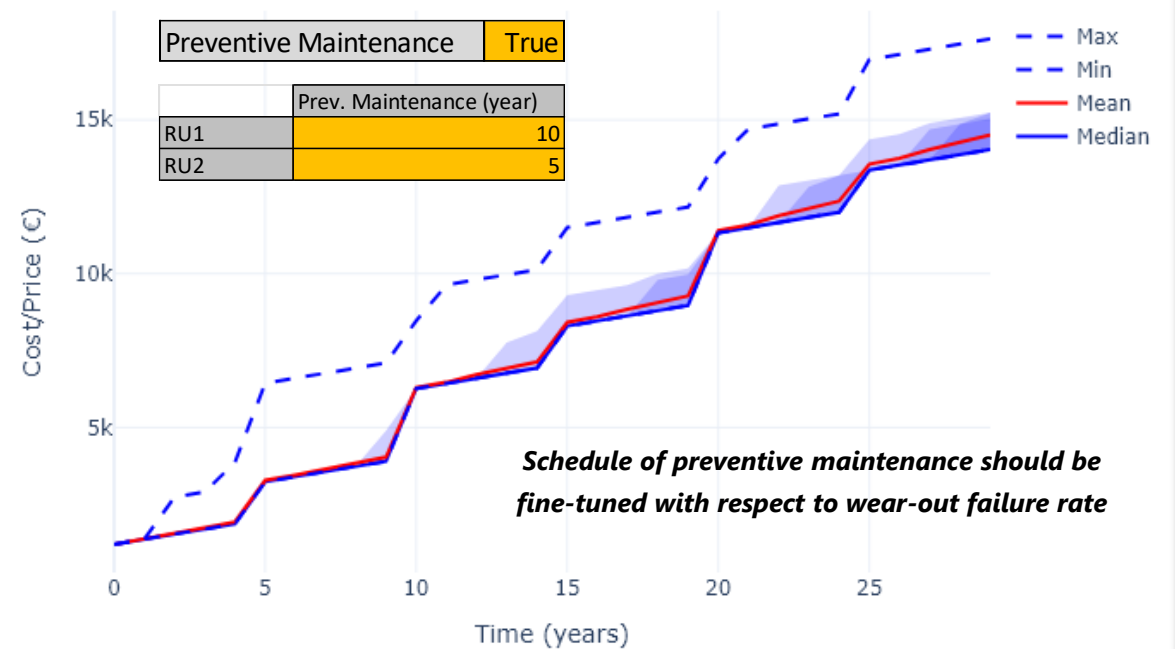
Cost of curative maintenance:

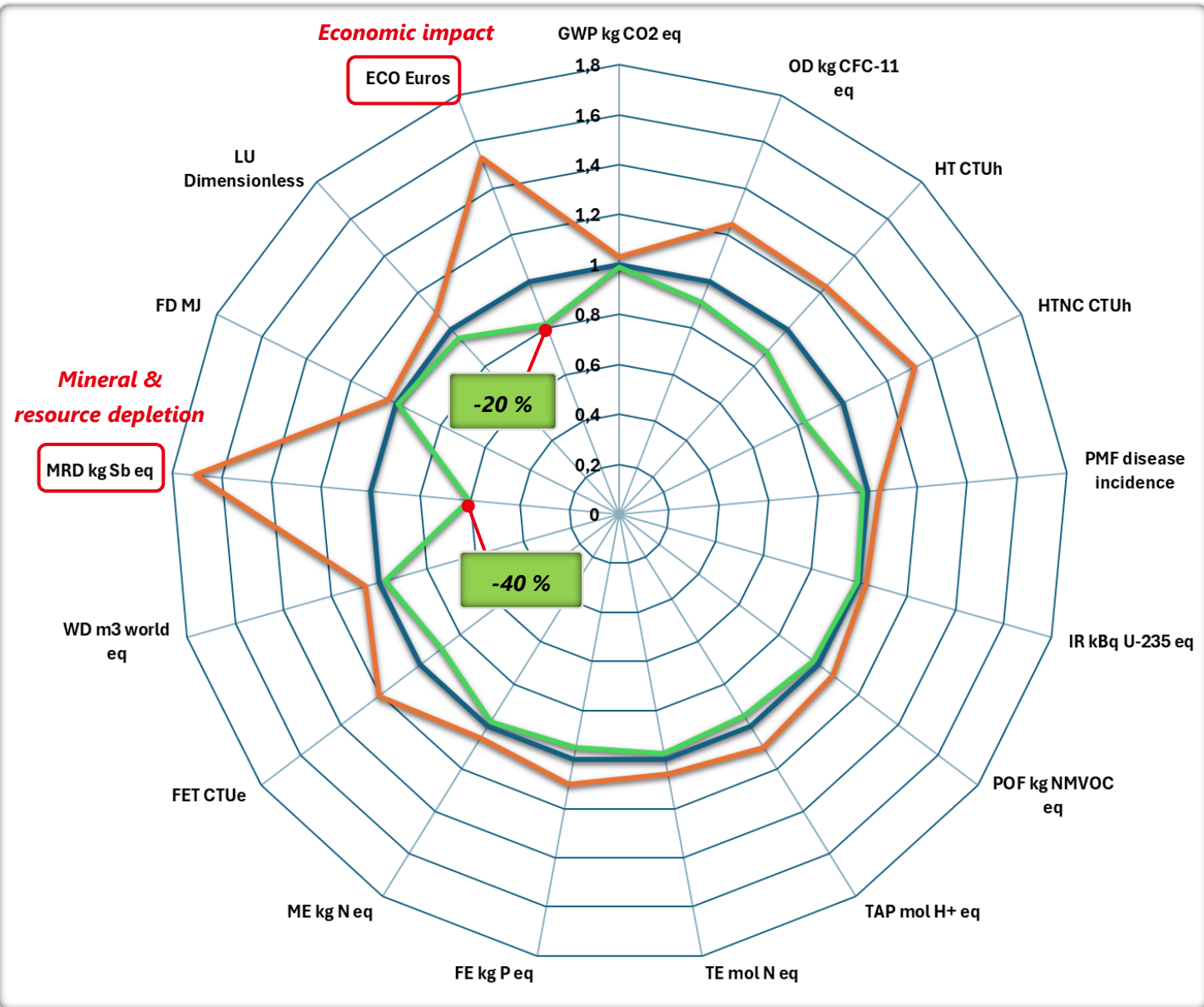
$$Cost_{RU_i} = \sum_i x_i \cdot (RU_{i_{RAW}} + RU_{i_{ASS}} + RU_{i_{DIS}})$$

Economic impact along system lifetime → System relying on curative maint.

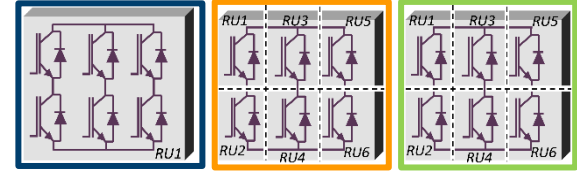


Economic impact along system lifetime → System relying on preventive maint.

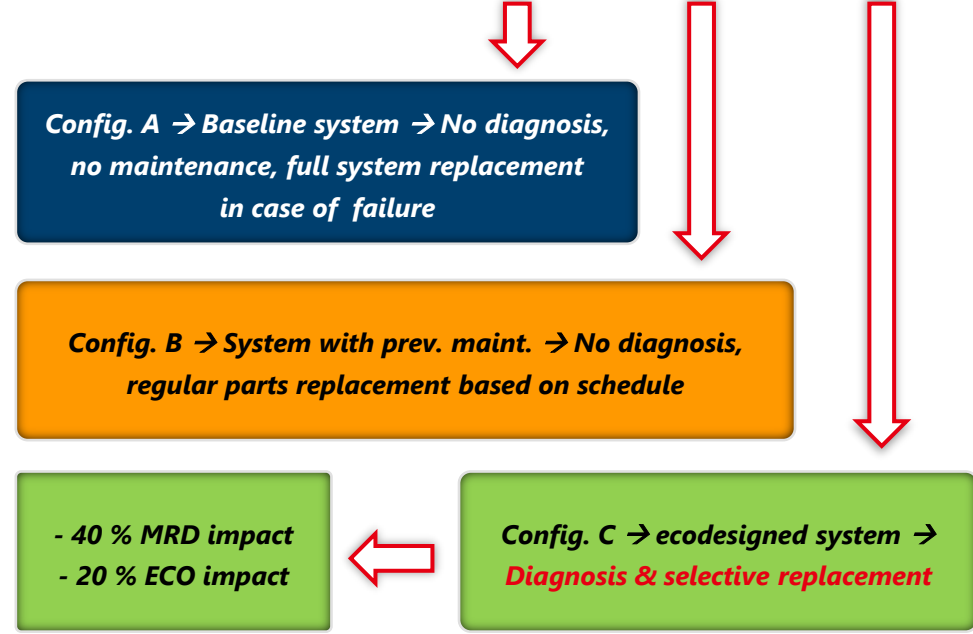




Life cycle impacts comparison of PE systems with fixed failure rates & different repairability configurations



System config.	A	B	C
Dismountability	0	1	1
Curative Maint.	0	0	1
Preventive Maint.	0	1	0



- 1. Introduction – LCA Framework & Key drivers of LCA in Power Electronics (PE)**
- 2. Some Recent Studies on LCA of PE**
- 3. LCA at Mitsubishi Electric**
- 4. Sub-parts Manufacturing Impacts Assessment**
- 5. Systems Life Cycle Impacts Assessment – PELCA software**
- 6. Take-away Messages & Perspectives**

- **Critical need for assessment & reduction of environmental impacts of power electronic systems**
- **LCA is a powerful tool to :**

Design systems with limited environmental impacts

Reduce dependency to critical raw materials

Anticipate customer demands and/or legal obligations

Design 'fit-for-usage' systems

Raise awareness on ecological costs of hardware

- **LCA should be used as a design tool starting from the early stages of product development** → env. impact should be seen as a complementary performance indicator
- **LCA has limits :**

ISO-standardized method but flexible system boundaries

Scarcity of available & accurate data

Discrepancies among LCA databases

End-of-Life (EoL) scenarios

- Key importance of **data sharing and communication between stakeholders** to strengthen the existing models and consolidate their results → Need for **stronger collaborative approaches & tools**

- **MERCE is currently developing parametric LCA models at different scales of analysis** and considering the **different stages of PE systems lifecycle**
- MERCE contributions to the PE community, in an **open-source mindset** :
 - Sharing of **manufacturing LCI models**
 - **PELCA as a potential collaborative LCA software platform**
- MERCE is open to the integration in PELCA of relevant add-ons, providing more added value to this collaborative LCA tool dedicated to power electronics

PELCA Software Overview

Main purpose	Research
Ease of use	Yes → No specific software skills
Potential of evolution	Yes → Open-source + collaborations
Ecodesign features	Lifecycle staircase approach Faults & diagnosis (curative maint.) Modularity / Dismountability Preventive maintenance Economic impact

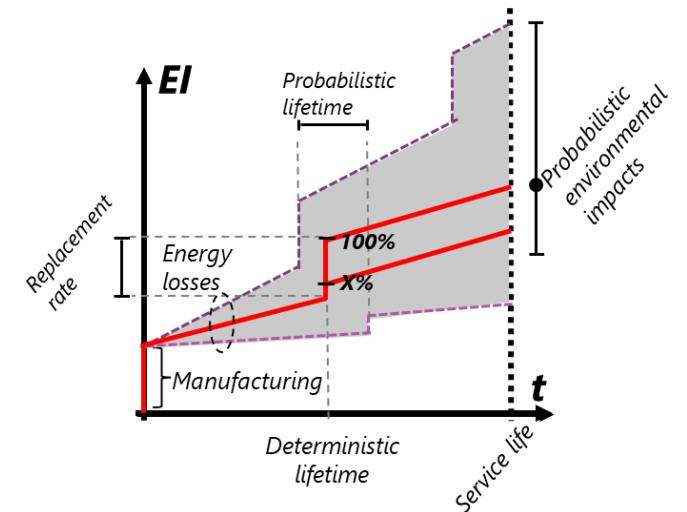
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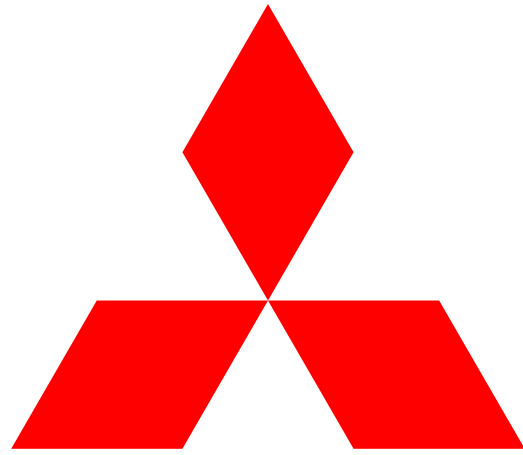


<https://github.com/merce-fra/PELCA>



**PELCA : a collaborative LCA tool
for the research community**





**MITSUBISHI
ELECTRIC**

Changes for the Better