Pulsatec workshop: Sarrebrücken

Life-cycle and techno-economic analyses

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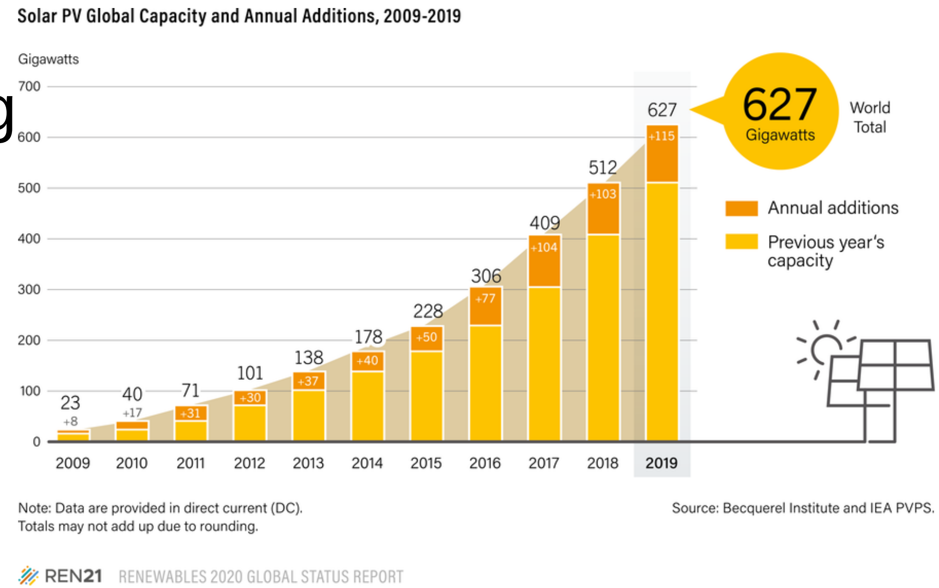
Presentation structure

- Introduction
- Economic and environmental assessment
- Uses and coatings case studies:
  - Identification of problematic aspects
  - Decision-making
  - Optimization/parametrization
- Perspectives and conclusions

Introduction

- Thin films are becoming more prevalent than ever

… and there is a need for environmental accountability!



[1]

➔ Applying assessment techniques to deposition processes

- Joint economic and environmental assessment

[1] Reve news : *https://www.evwind.es/2020/07/05/in-2019-the-solar-pv-market-increased-an-estimated-12-to-around-115-gw/75561*

Economic and environmental assessment

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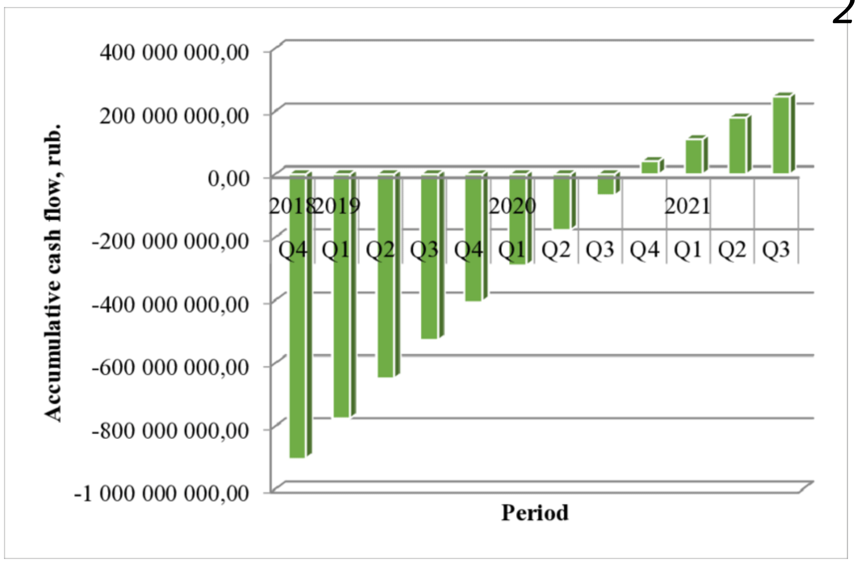
Economic assessment

- Many techniques for economic assessment:
  - Techno-economic analysis (TEA), Life Cycle Costing (LCC), Net-Present Value (NPV), Cash Flow Analysis (CFA) …

- Use for industrials or business owners fairly straightforward:

  Profitability assessment



[2]

[2] Morozovskiy, P. et al., 2019. Cost effectiveness indicators of residential complex construction project. E3S Web of Conferences 91:08060 DOI:10.1051/e3sconf/20199108060

Environmental assessment

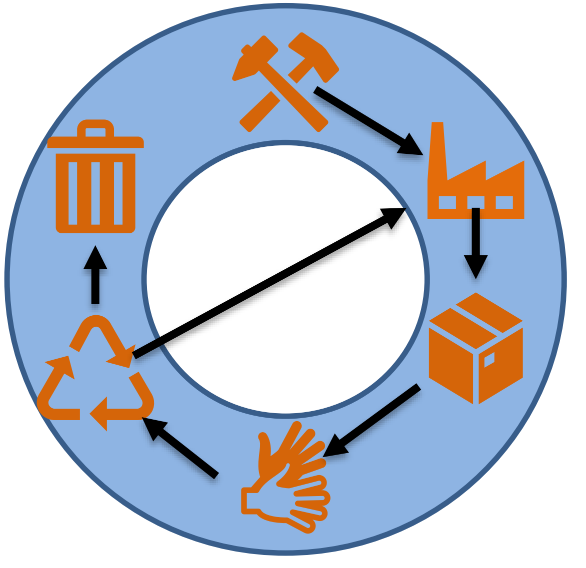
- As many techniques for environmental assessment:
  - Life-cycle assessment(LCA), Material Flow analysis(MFA), Environmental Impact Assessment (EIA), Carbon footprint …

- Use for industrials or business owners:

  -Ecolabel obtention

  -Environmental norms regularisation

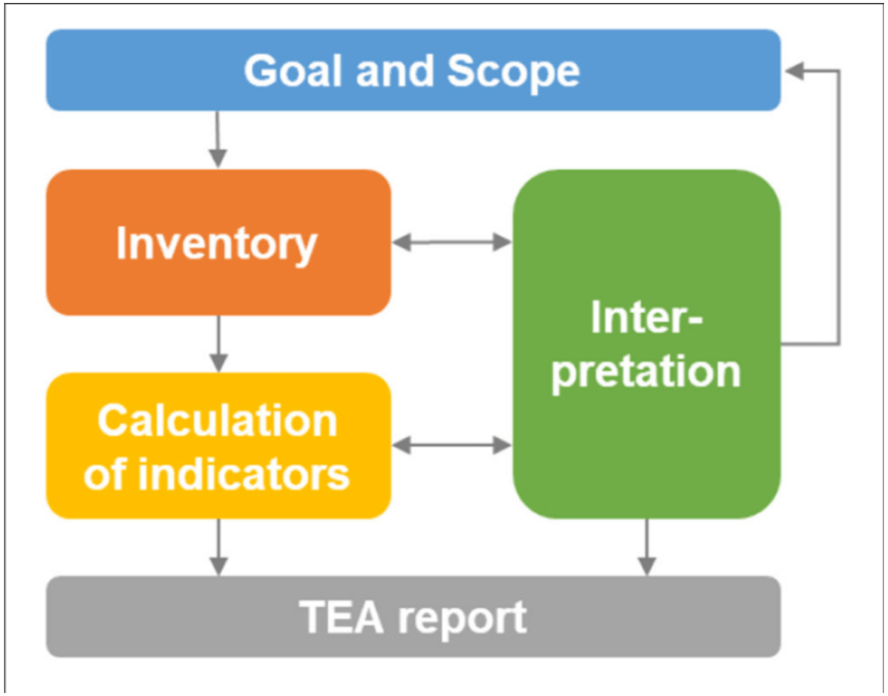
  -Assessment of future damage costs (CO2 tax…)



Techno-economic analysis (TEA)

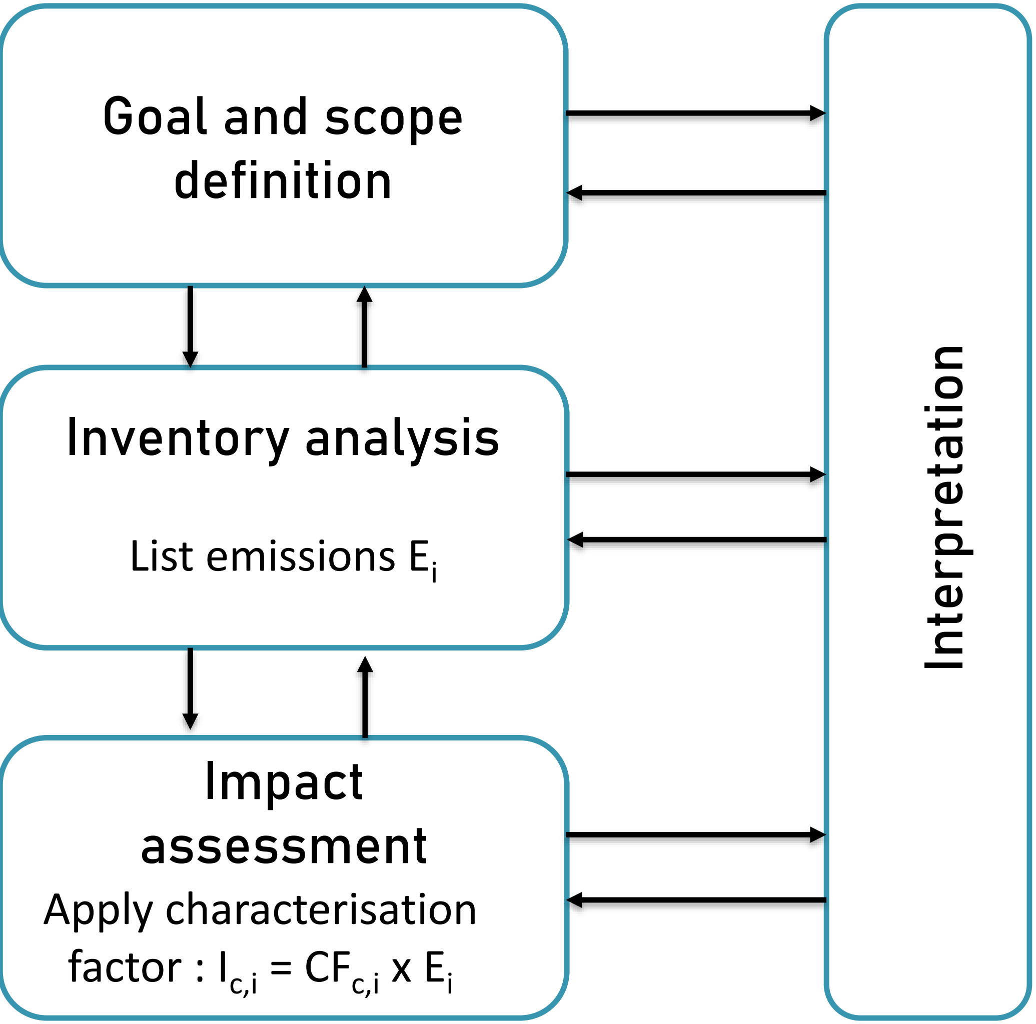
- Evaluation and aggregation of Capital Expenditures (CAPEX) and Operational Expenditures (OPEX)

- Single cost per functional unit (F.U.)



➔ Useful to compare competing technologies

Life-cycle assessment (LCA)



- Listing of emissions
- Whole life cycle
- Assignment of CF to emissions in ≠ impact categories

➔ Obtention of impacts per F.U.

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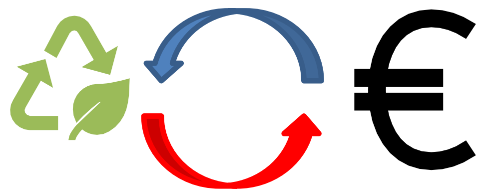
Why joint LCA and TEA?

- Joint assessment ➔ Nuanced multicriteria approach
- Trade-offs



- LCA : many aspects of the process are taken into account
- TEA : useful single cost indicator

➔ Symbiotic relationship between both methodologies: same goal and scope, F.U., inventory, …

Uses for joint TEA-LCA

- Demonstration of 3 different applications for joint TEA-LCA:

1. Identification of problematic aspects
2. Decision-making
3. Parametrization/Optimization

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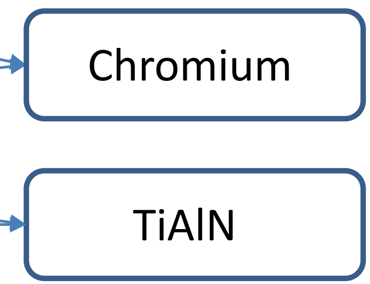

- Two case studies:
  - Replacement of electrodeposited chromium
  - HiPIMS for TiAlN coated tools

Applications and case studies

1. Chromium coatings:
Identification of problematic aspects

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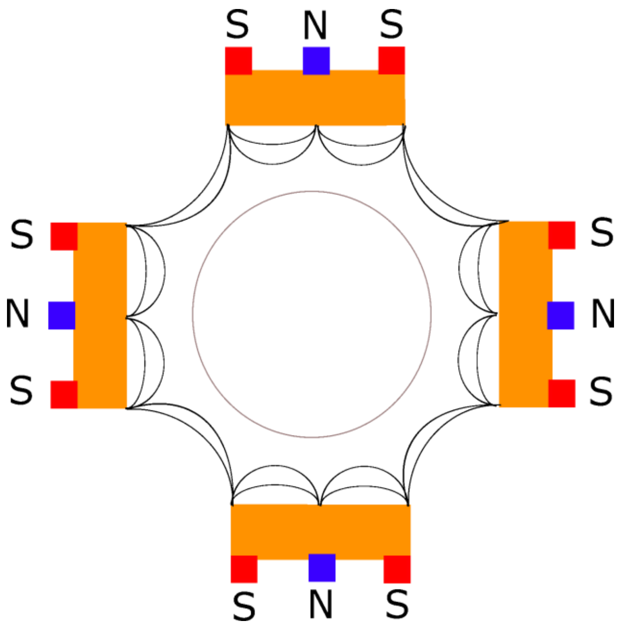
Hard chromium

- Compare impacts of chromium coatings of 20µm on a cylinder of 80 cm X Ø 40 cm => Functional Unit (F.U.)



- Two technologies: Magnetron-sputtering (MS-DC) and electrodeposition (ED)

Main processes differences

- Environmentally:
  -Close to no emissions for MS-DC
  -Higher energy consumption
  -Different production path for metallic chromium and chromium oxide (kinda…)

- Economically:
  -Higher investment cost for MS-DC
  -Lower productivity (17µm/h vs 25µm/h)
  -Less labour for pre- and post-treatment needed (15 min vs 30 min)

Methodology

- LCA to determine environmental impacts of both processes

- Use of common inventory for TEA

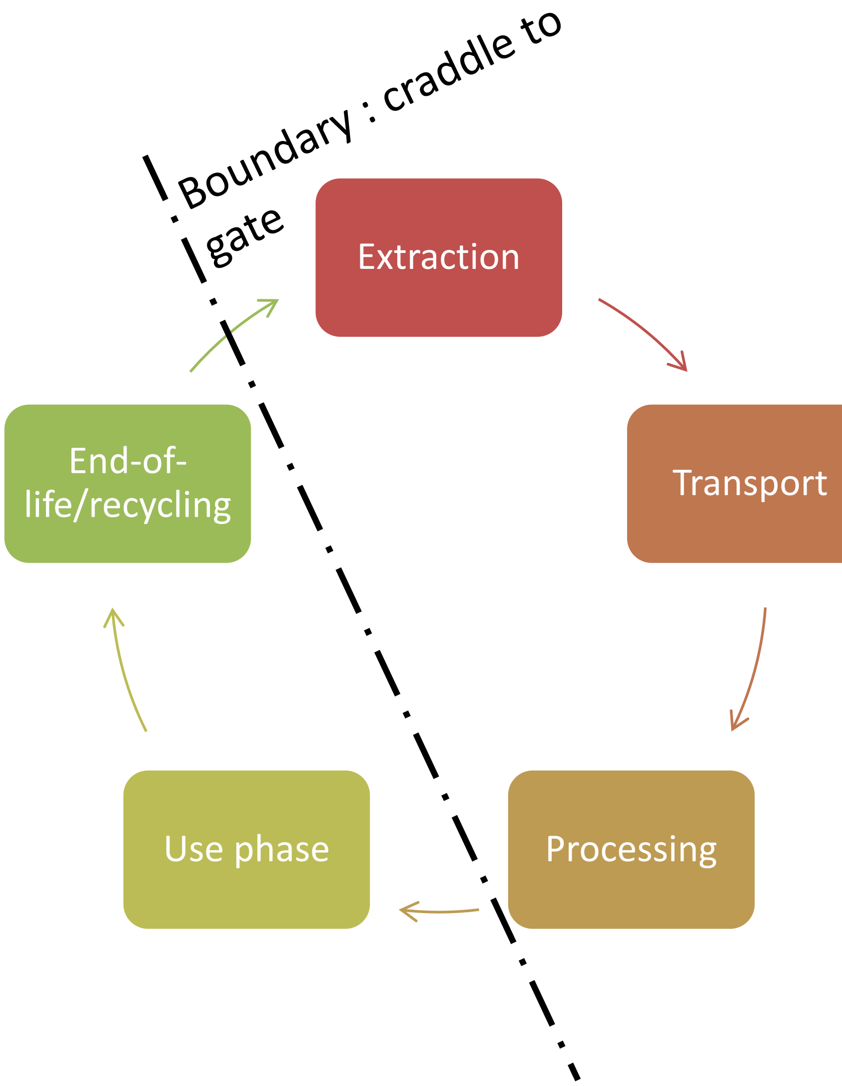
- Simapro v9 used
  - EcoInvent database
  - Method ReCiPe 2016 (Hierarchist configuration)

Study scope

- Scope: from craddle to coating production

- Not taken into account:
  - Cylinder (substrate) production
  - Transport
  - Equipment manufacture
  - Coated cylinder use phase

- Belgian electricity mix



Inventory : electrodeposition

- Extrapolated and adapted from litterature

Coating

Flow	Amount	Unit	Source
Electricity	**20.2**	**kWh**	**Present work**
Chromium oxide	**298.5**	**g**	**Present work**
Sulfuric acid	0.17	g	(Krishnan et al., 2008)
Water	332	L	(Rodriguez, et al., 2018)
Airborne Cr^{VI} emissions	**25.1**	**mg**	**(US EPA, 1996)**
Waterborne Cr^{VI} emissions	**54.5**	**mg**	**(Rodriguez, et al., 2018)**
Lubricating oil	28	g	(Rodriguez, et al., 2018)

Wastewater treatment

Flow	Amount	Unit	Source
NaOH	26	g	(Rodriguez, et al., 2018)
SO_2	18	g	(Rodriguez, et al., 2018)
Sulfuric Acid	54	g	(Rodriguez, et al., 2018)
MgO	29	g	(Rodriguez, et al., 2018)
Water	19	L	(Rodriguez, et al., 2018)

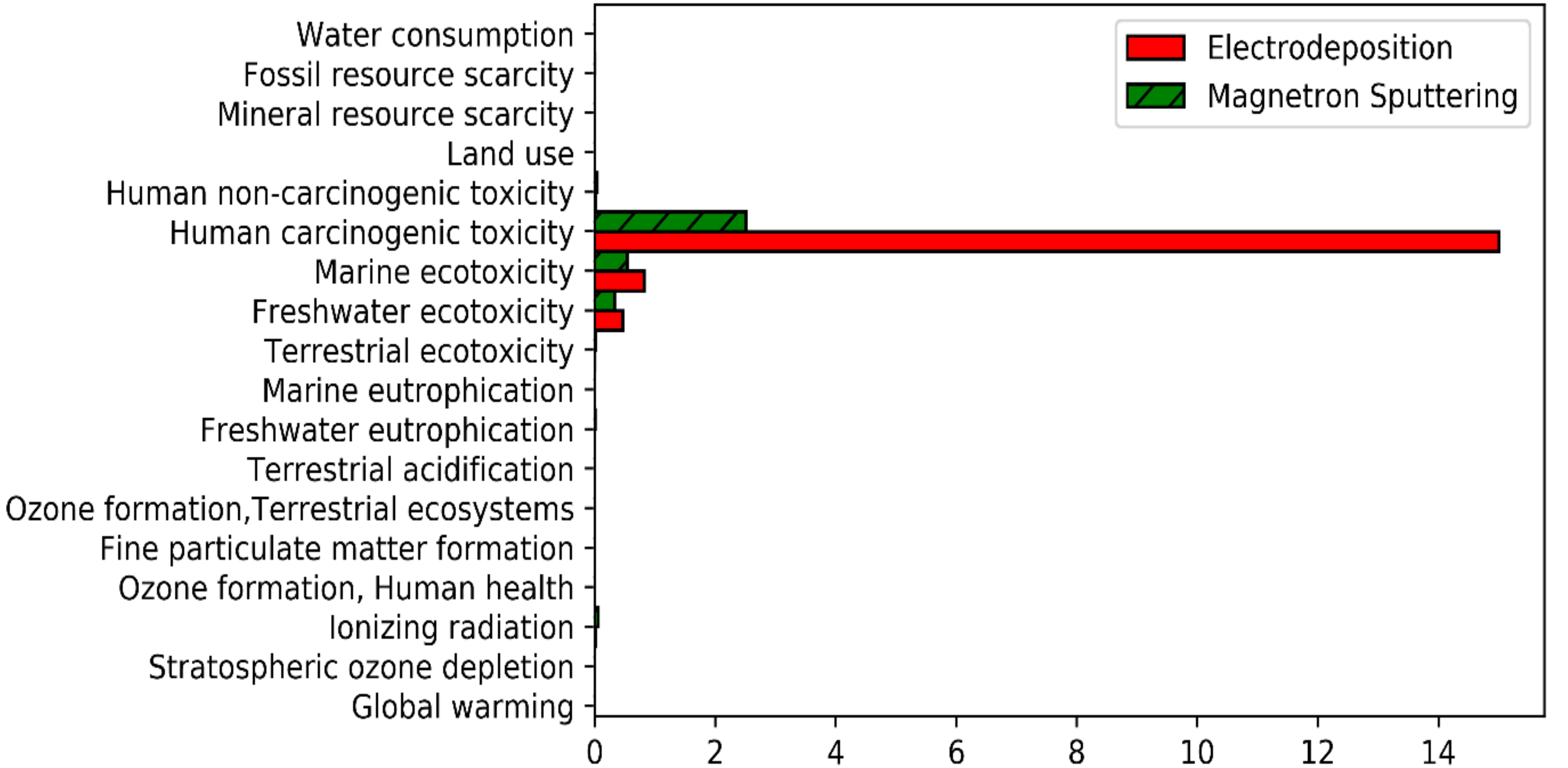
Inventory : DC-MS

- Extrapolated and adapted from litterature

Coating

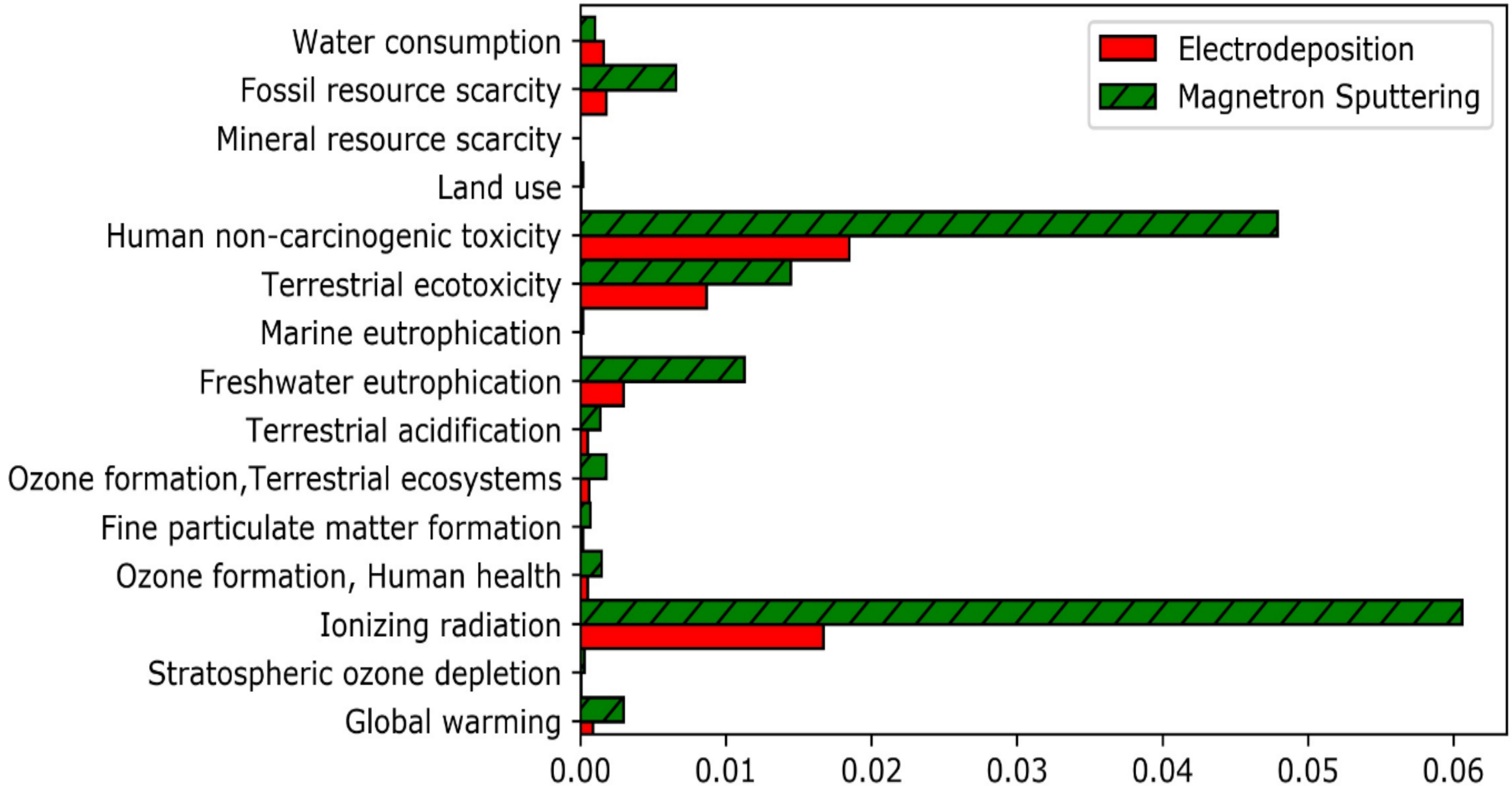
Inputs	Amount	Unit
Argon	25.12	g
Tap water	8	kg
Isopropanol	0.2	kg
Chromium	**0.1685**	**kg**
Electricity mix, BE	**71.76**	**kWh**
Outputs		
Argon (to air)	25.12	g
Chromium (to soil)	25.5	g
Water to sewer	8	kg

Normalized impacts



- Normalization factor: global annual average emissions for 1 person in 2010 ➔ Detect outlying categories

Normalized impacts– no carc. tox.



Results

- Toxicities most problematic

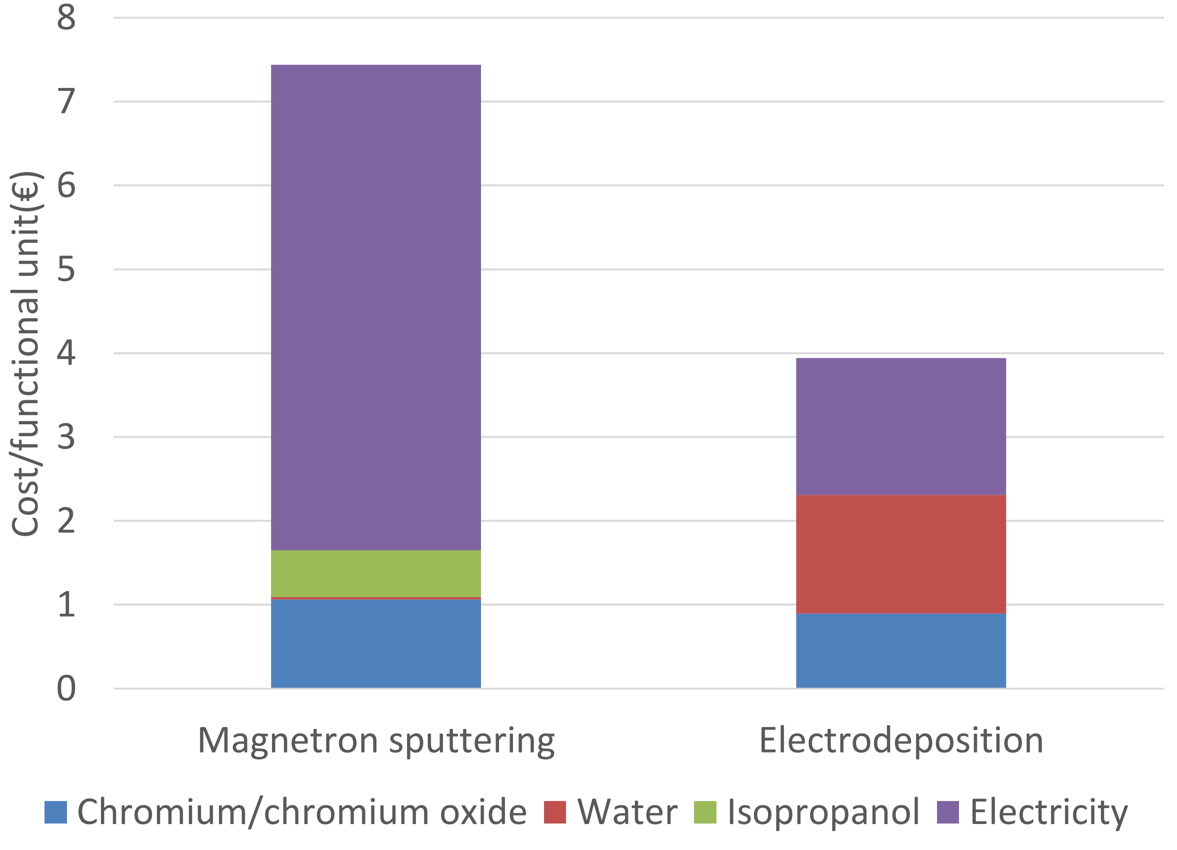
- Cr^{VI} extremely carcinogenic ➔high normalized impact

- Other impacts correlated with electricity consumption

➔ Two main problems: Cr^{VI} emissions and electricity consumption

Cost assessment

Consumables costs more important for MS-DC (7.46€ vs 3.96€)



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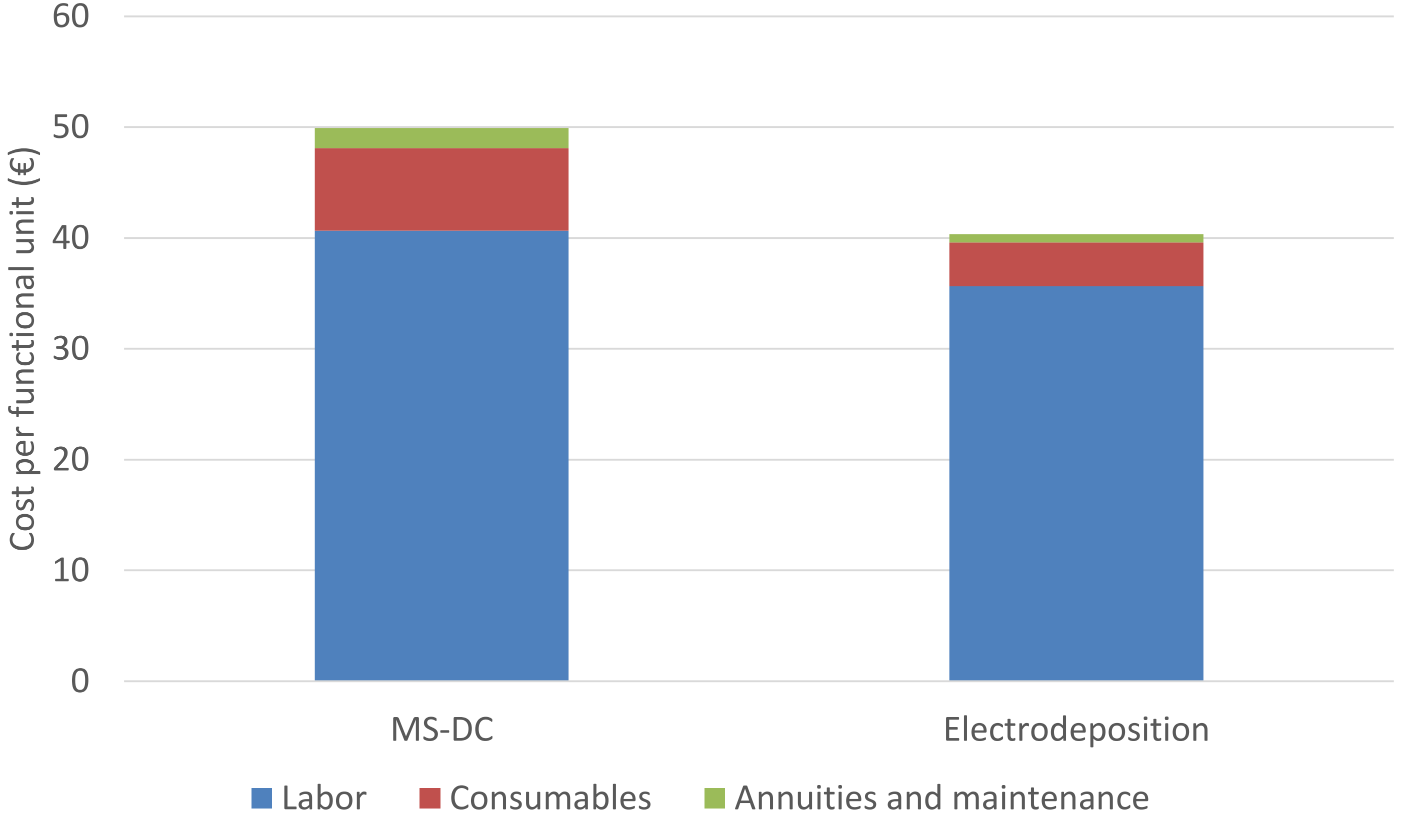
Cost assessment

However, main cost is labor (in NW EU)
(49.91€ vs 40.35€)



Applications and case studies

2. Chromium coatings:

Decision-making

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PVD a viable alternative for hard chromium?

- Probably not 😩

- Except if specific conditions are met:
  - High degree of automation
  - Low carbon impact of electricity mix
  - No need for repair operations

➔ Actually pretty good for thinner, decorative coatings!

- Better alternative for hard chromium: HVOF, f.e.

Complete results published in **Materials**:
Merlo Antoine, and Léonard Grégoire. 2021. "Magnetron Sputtering vs. Electrodeposition for Hard Chrome Coatings: A Comparison of Environmental and Economic Performances" Materials 14, no. 14: 3823. https://doi.org/10.3390/ma14143823

Applications and case studies

3. TiAlN:
Optimization/Parametrization

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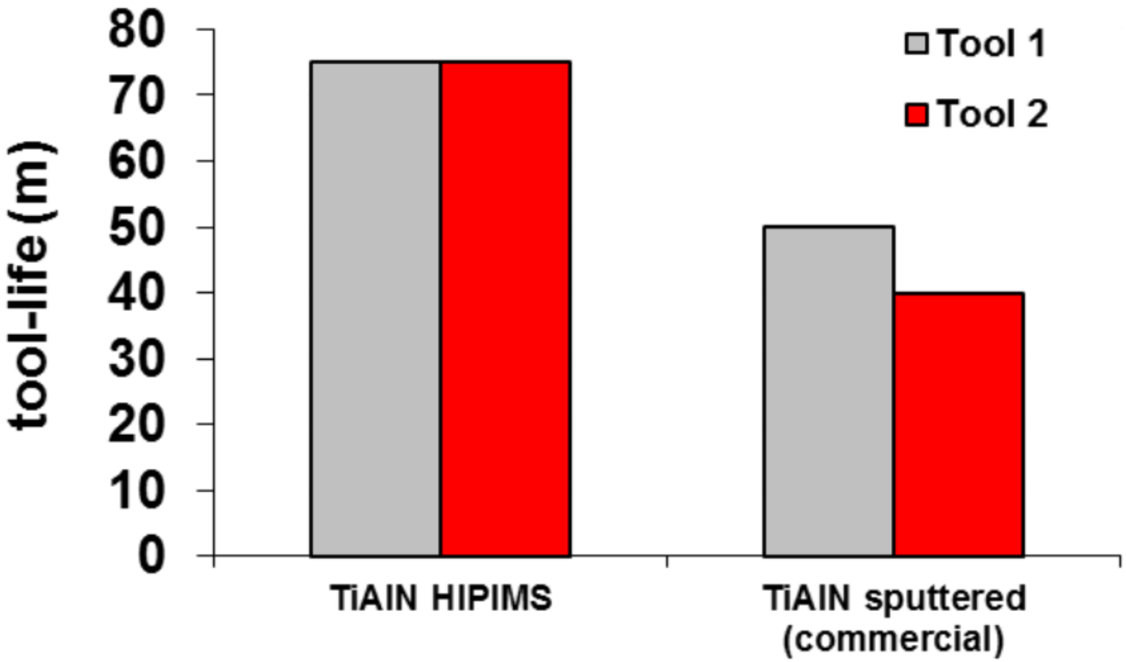
Goal

- HiPIMS: costlier, but better performing coatings than MS-DC
- Evaluate costs and impacts for both:
  - Coating phase
  - Cutting phase
- Higher tool life ➔ Lower downtimes ➔ Higher productivity and lower passive electricity consumption
- Joint evaluation of costs and environmental impacts

TiAlN and HiPIMS

- Higher performances of HiPIMS coatings → Improved tool life
- Good enough to compensate higher HiPIMS costs?



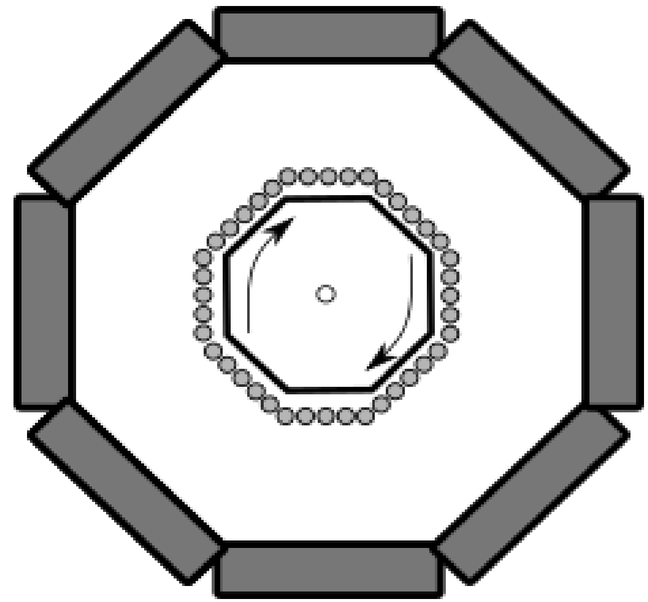
Weichart, J. (2012). 'Titanium aluminum nitride sputtered by HIPIMS', IOP Conference Series Materials Science and Engineering

Tools considered

- HSS milling tools: 8mm diameter, 8 cm length
- 4µm TiAlN
- Tool life of 75 min for HiPIMS and 50 min for MS-DC
- 1.8µm/h for HiPIMS
  3.6µm/h for DC-MS

Installations

- 200 tools per batch
- Rotating and heating substrates
- HiPIMS :1 300 000 €
  DC-MS :1 200 000 €
- Same consumptions for both processes but longer deposition time for HiPIMS (133 min vs 67 min)



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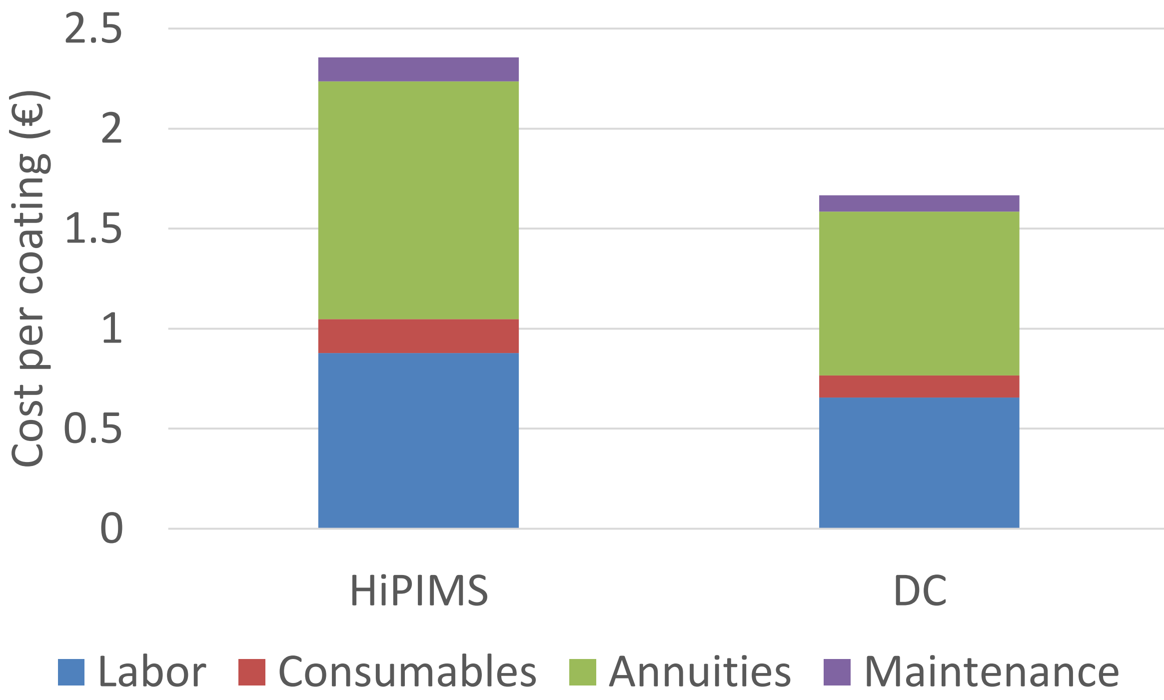
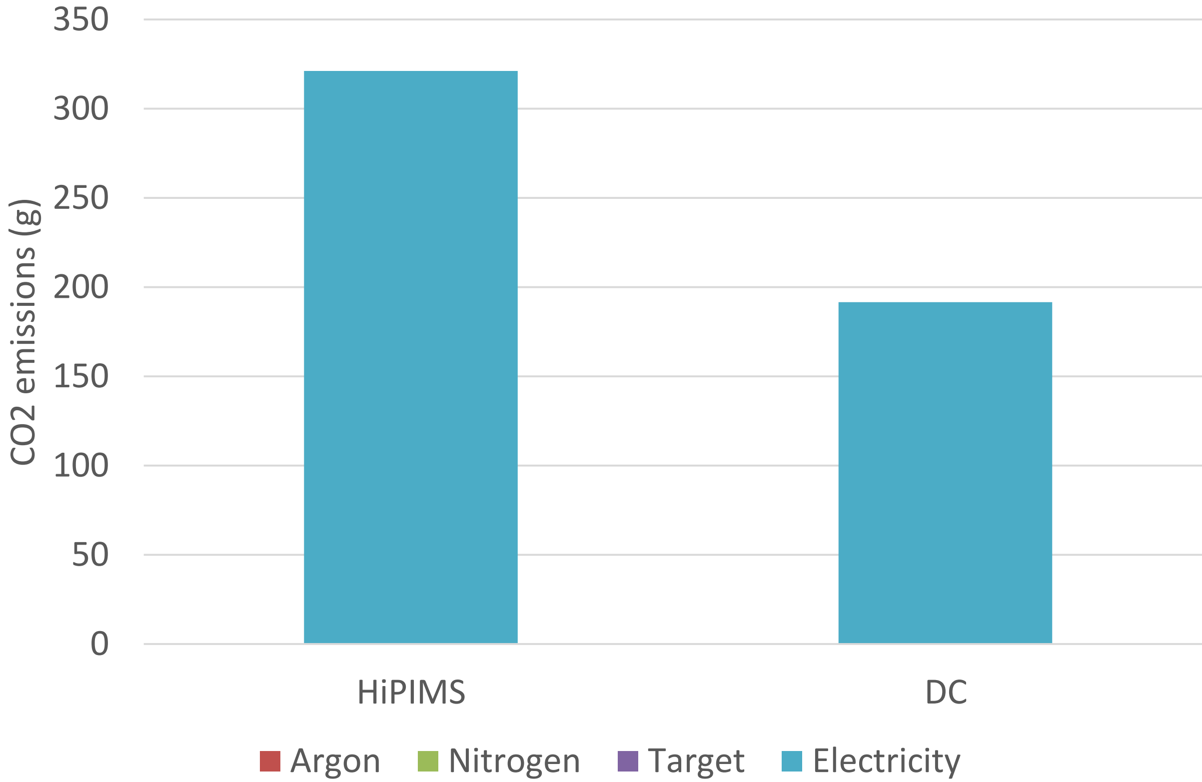
Cost evaluation

- Two 8h shifts per day (40€ per operator)
- 1464 vs 1094 batches a year (MS-DC vs HiPIMS)
- 0.08€/kWh
- 5 year payback



Environmental impact

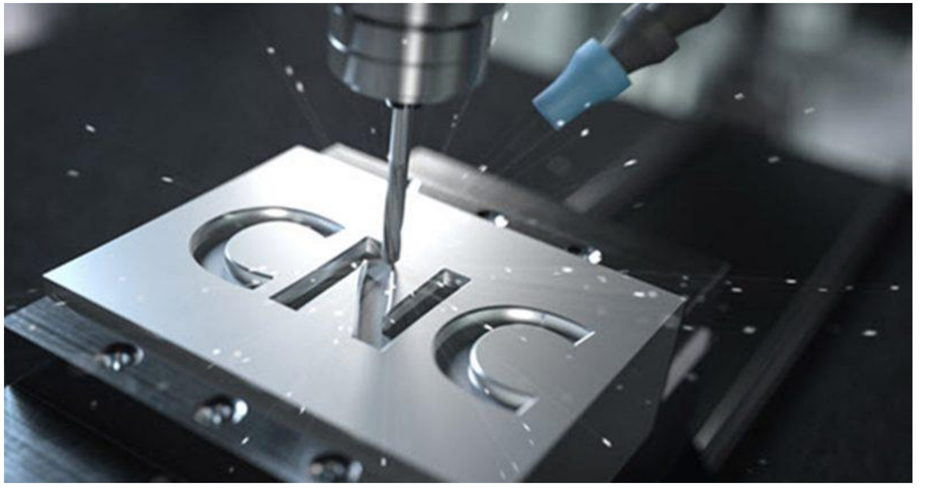
- CO2 emissions: 320.7 gCO2 for HiPIMS, 191.2 gCO2
- Electricity production is the main factor (Belgian EF: 174 gCO2/kWh



Cutting phase

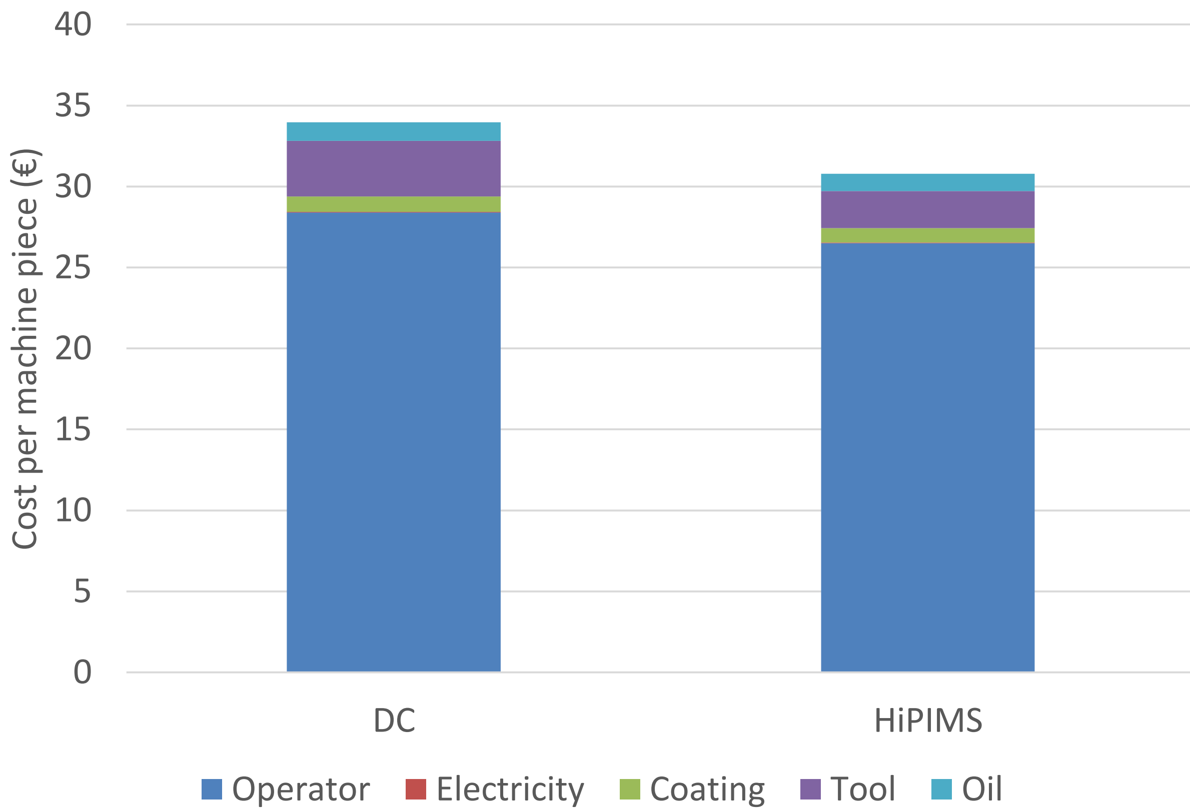
- Inclusion of costs and impacts of cutting phase:
  - Substrate
  - Coatings
  - Cutting fluid
  - Electricity consumed

  Tool life has an impact on those factors!



Cutting phase costs

- Longer tool life leads to lower down times ➔ Lower costs and higher productivity



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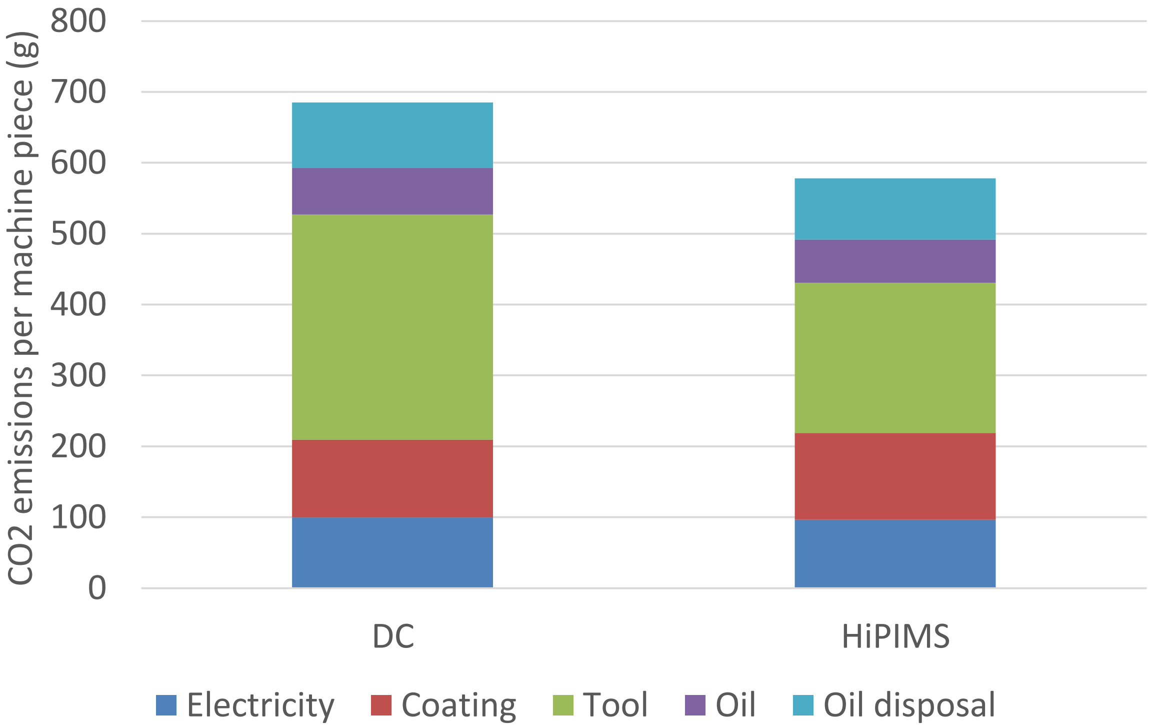
Cutting phase impacts

- Higher CO_2 emissions for HiPIMS coatings, but:
  - Less substrates used
  - Less cutting fluid
  - Less passive electricity usage



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Cutting phase evaluation conclusions

- Use of HiPIMS reduces the total cost by around 10% and CO_2 emissions by 15%

- High potential for HiPIMS technology

- Different operating parameters ?
  - Lubrification conditions
  - Cutting speed

Costa, Eder & Bacci Da Silva, Marcio & Machado, Alisson. (2009). Burr Produced on the Drilling Process as a Function of Tool Wear and Lubricant-Coolant Conditions. Journal of The Brazilian Society of Mechanical Sciences and Engineering - J BRAZ SOC MECH SCI ENG. 31. 10.1590/S1678-58782009000100009.

Parametrisation: Taylor's equation

- Parametrisation of cost and CO_2 (2 objectives)
- $VT^n = C$ ➔ Use cutting speed as a parameter

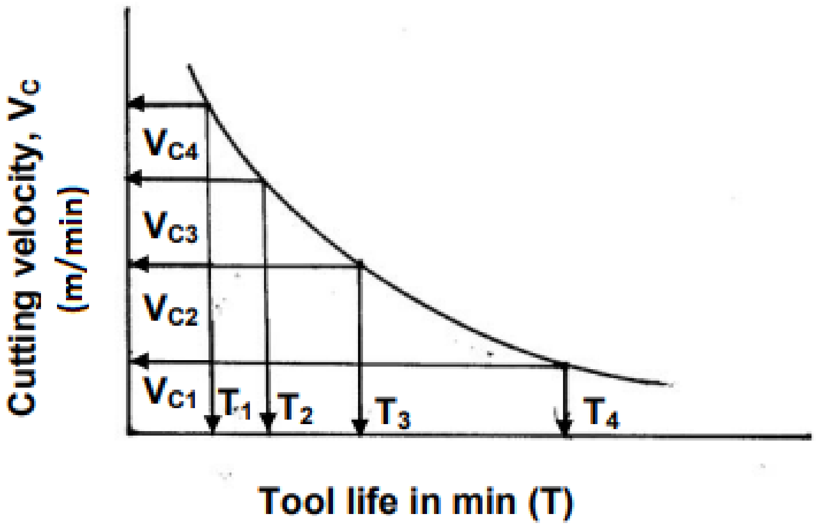
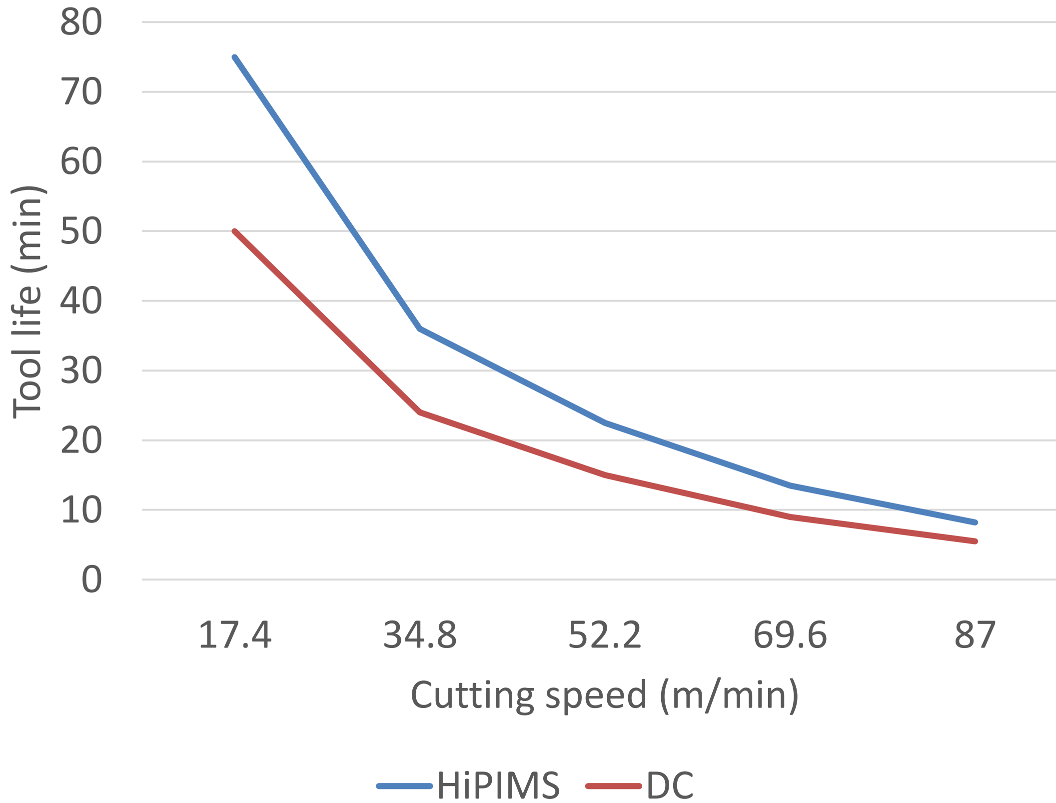


Figure 2: Cutting velocity - tool life relationship

Parametrisation: Taylor's equation

- Until experimental data, assumed that tool lives and powers evolve with speed as in *

- $$\frac{T(2V)}{T(V)} = \frac{T\prime(2V')}{T\prime(V\prime)}$$



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*Li, C. (2015). 'A quantitative approach to analyze carbon emissions of CNC-based machining systems', Journal of Intelligent Manufacturing 26, pp. 911-922

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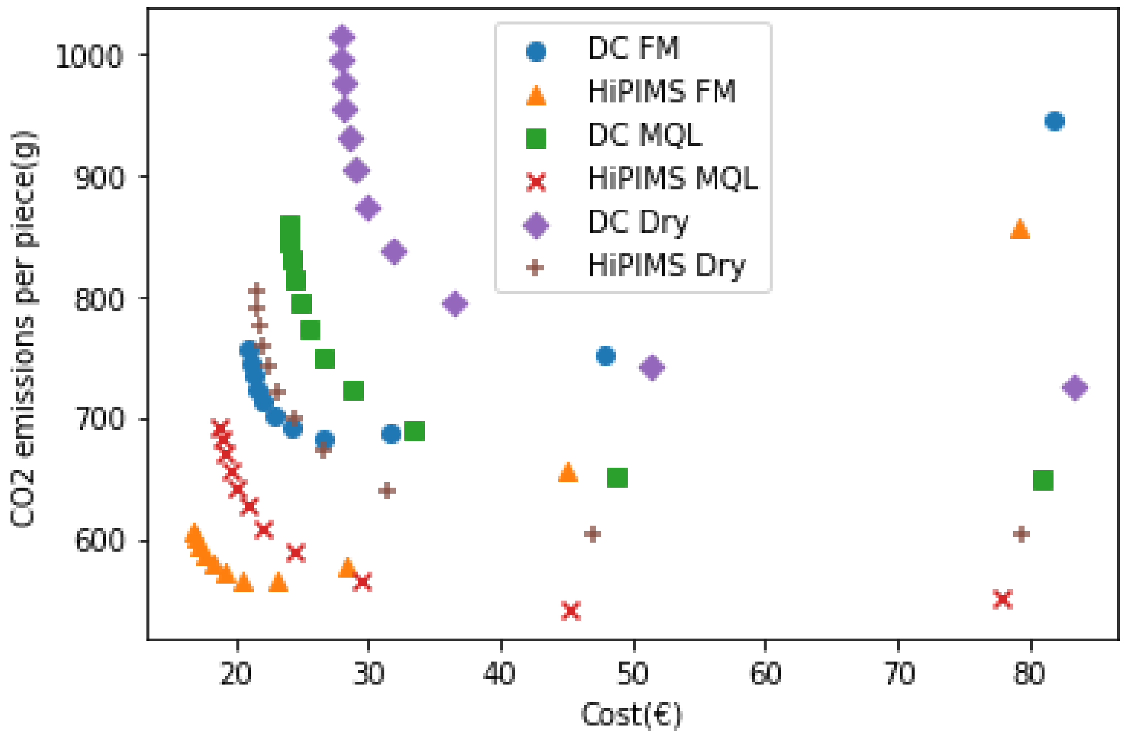
Parametrisation

- Plot of CO_2 emissions vs costs
- Several lubrication scenarios
- Cutting speed varies between 5 and 100 m/min



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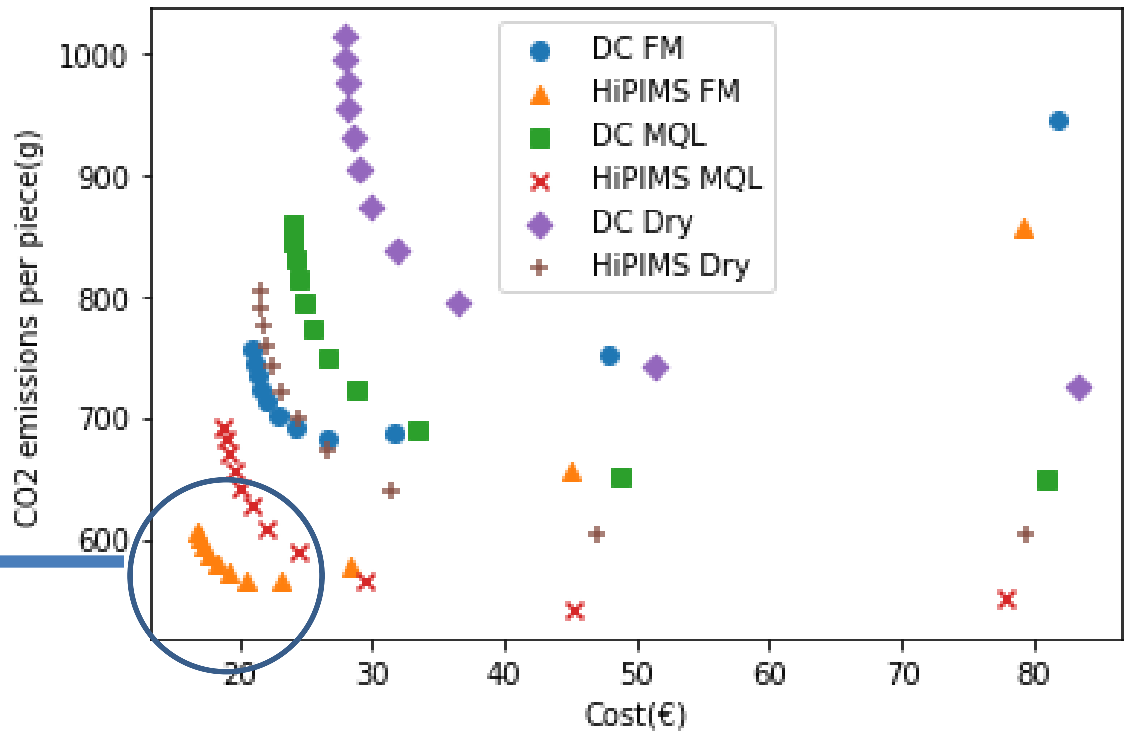

HiPIMS lowers both costs and CO2 impacts !

Parametrisation

- Plot of CO2 emissions vs costs
- Several lubrication scenarios
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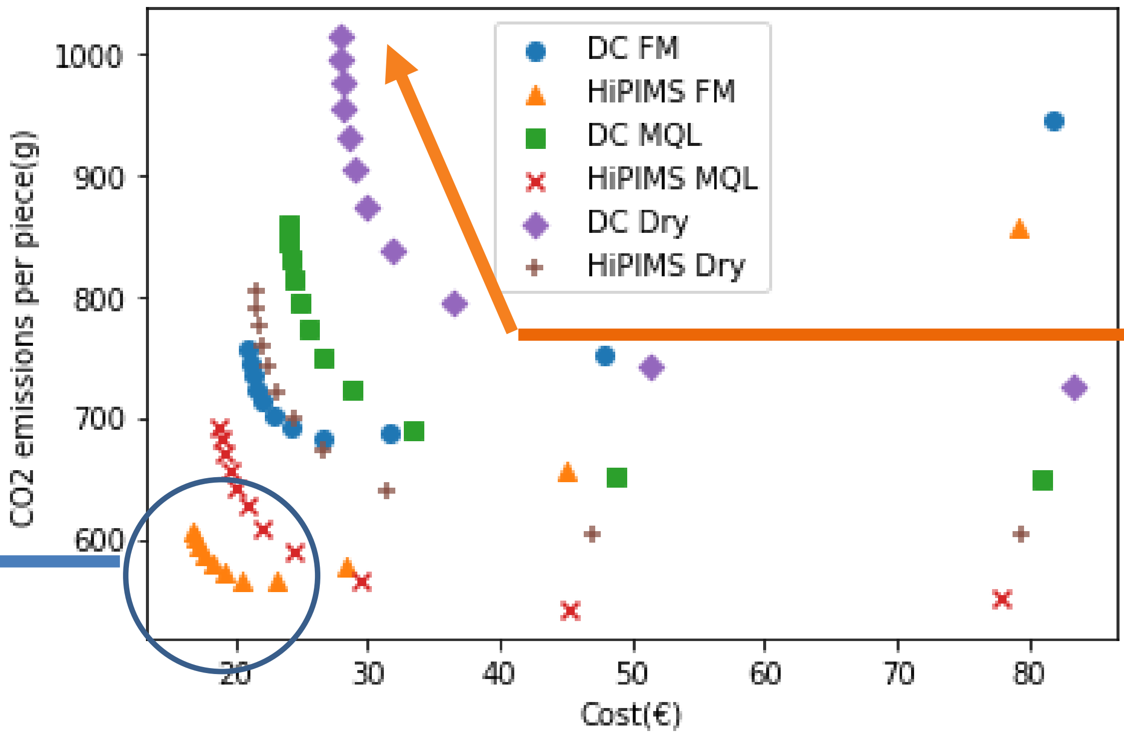


Cutting speeds reduce costs, but increase CO2 emissions

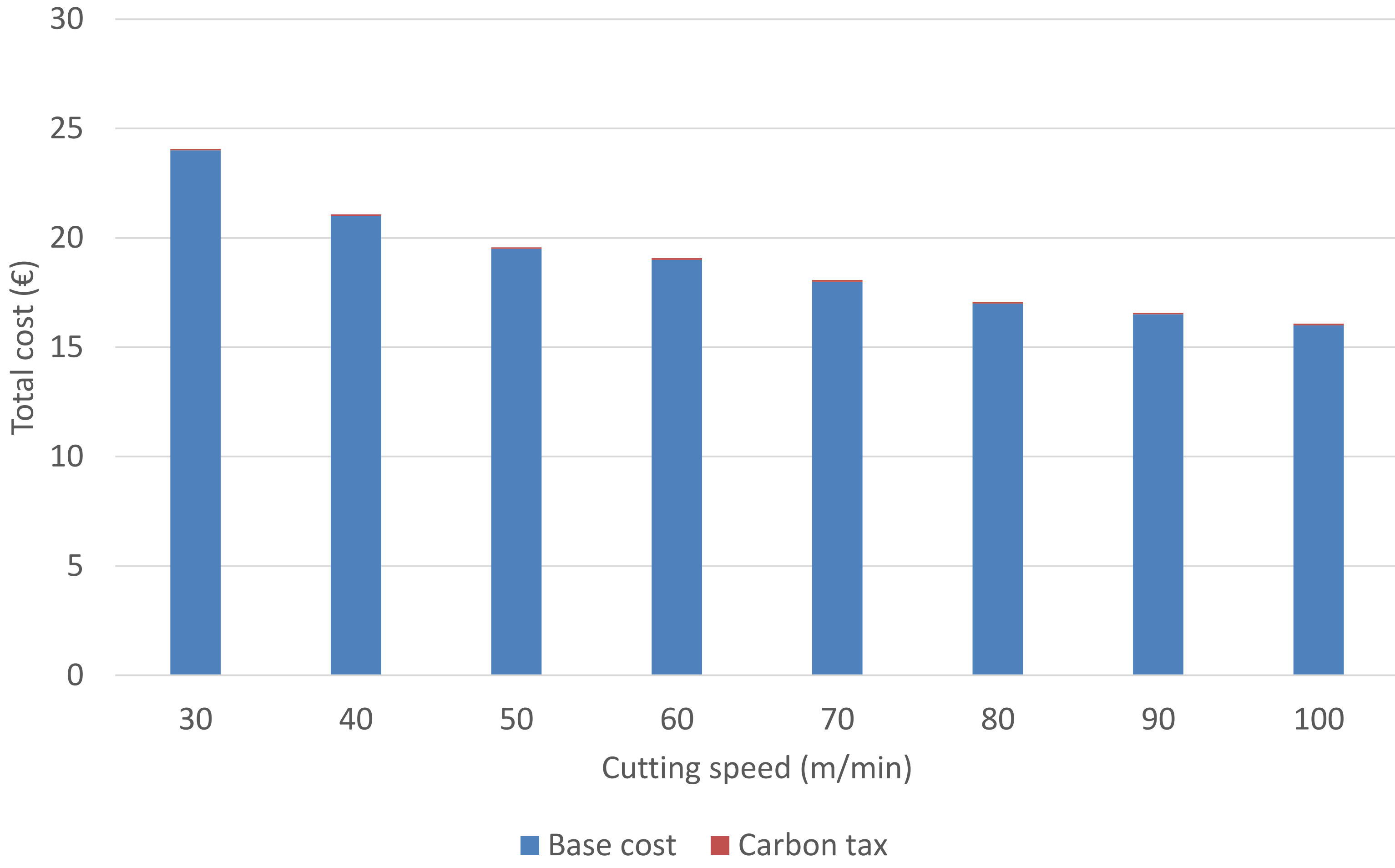
HiPIMS lowers both costs and CO2 impacts !

Parametrisation conclusions

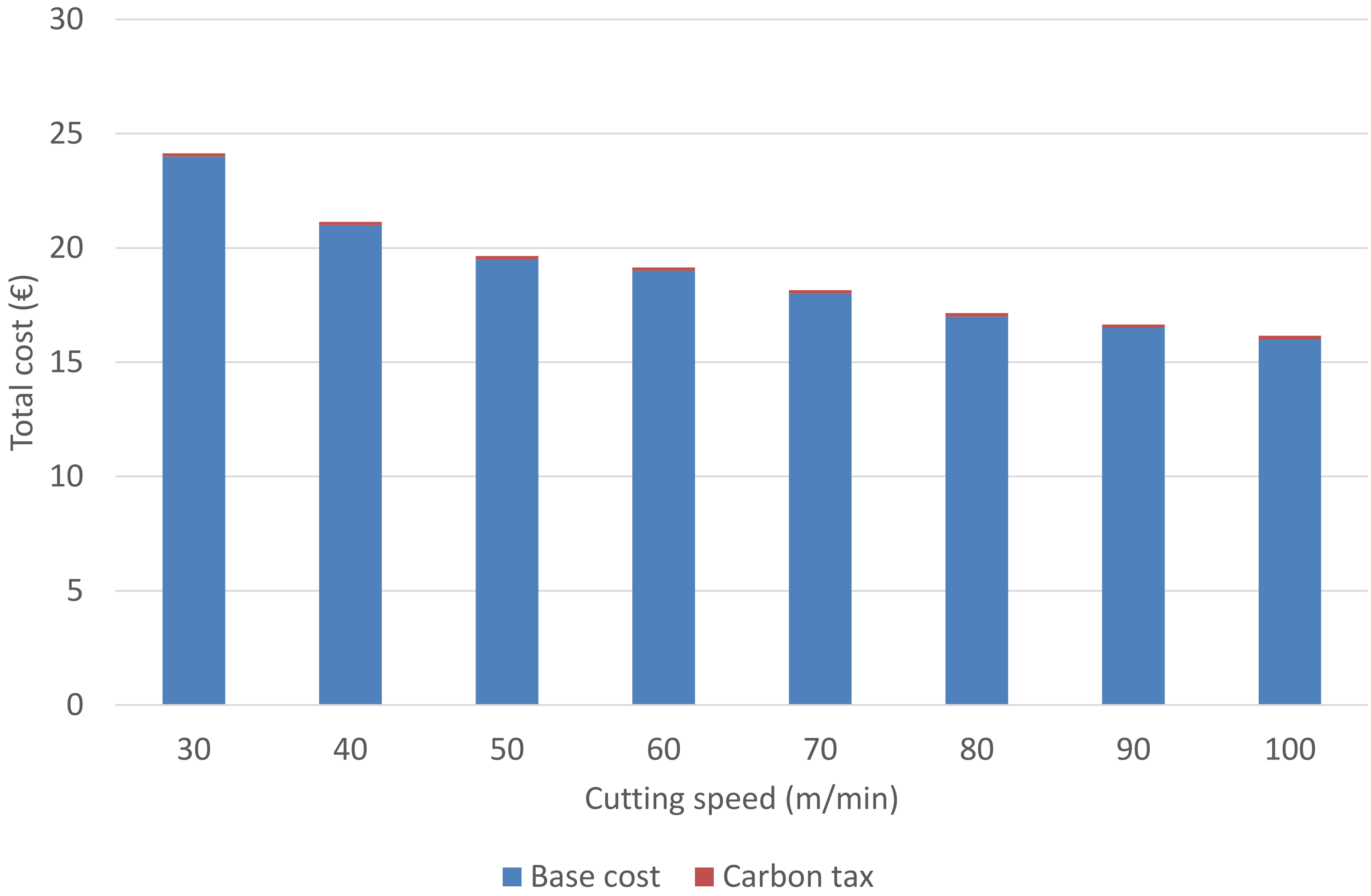
- HiPIMS in flood machining conditions seems to bring the best outcomes for both costs and CO_2 emissions
- Trade-offs between CO_2 emissions and costs
- How to choose the best cutting speed?

➔ Aggregation of CO_2 emissions via a carbon tax

Carbon tax: 120€/tCO2



Carbon tax: 250€/tCO2



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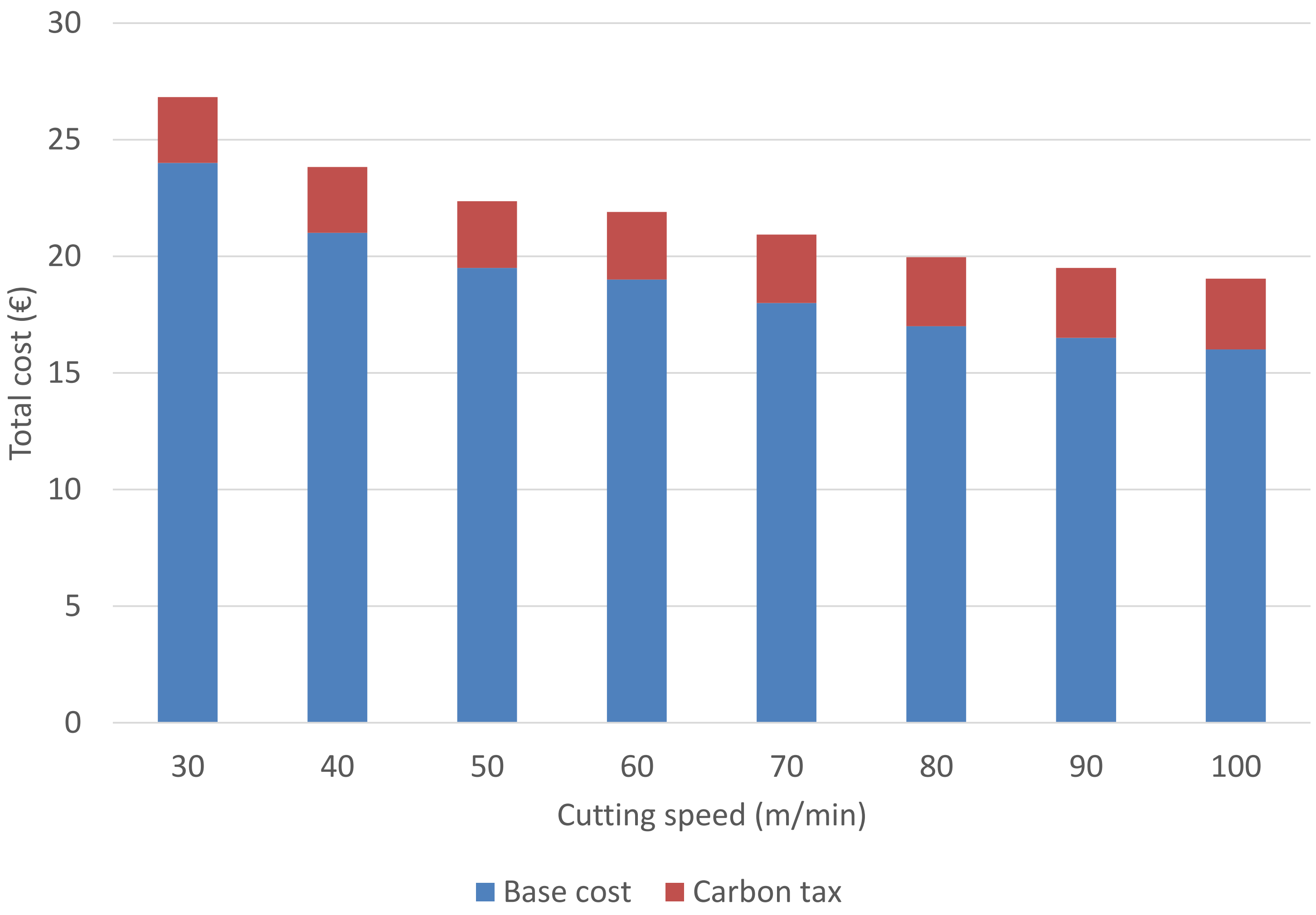
Carbon tax: 5000€/tCO2



TiAlN Conclusions

- CO_2 emissions differences are negligible, even with aberrant carbon taxes
- HiPIMS in FM at high machining speeds seem to be the best option
- Need of experimental data to validate assumptions

Conclusions and perspectives

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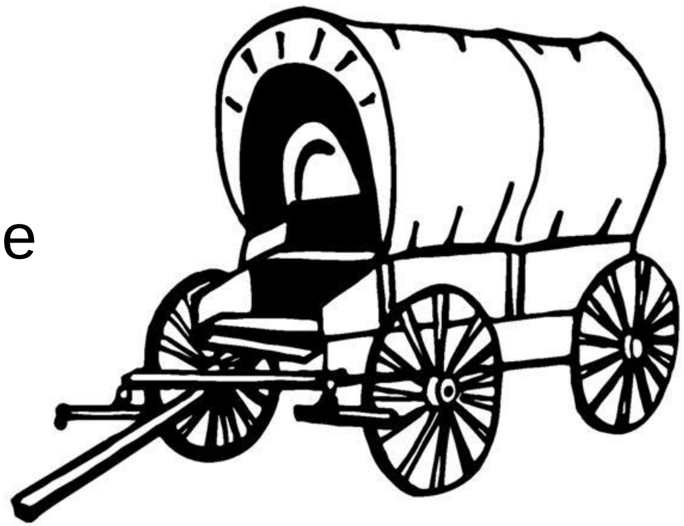
Conclusions

- Economic and environmental assessment methods can be used for coatings
- Joint use allows for a nuanced and complete approach
- Many options are still left on the table for joint assessment



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Thanks for your attention!

Références

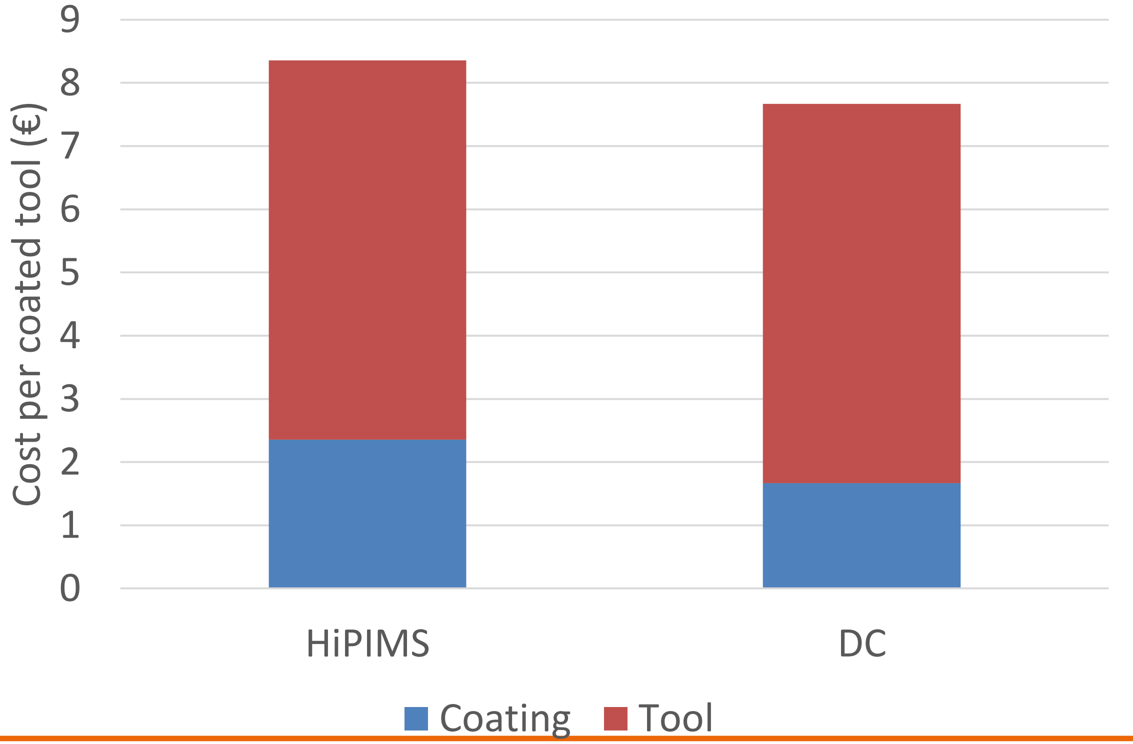
- [1] IndustryArc (2021). ‘Cutting Tools Market - Forecast(2021 - 2026)’
- [2] Bobzin, K. (2016). ‘High-performance coatings for cutting tools’, *CIRP Journal of Manufacturing Science and Technology*
- [3] Jindal, P.C. et al. (1999). ‘Performance of PVD TiN, TiCN, and TiAlN coated cemented carbide tools in turning’, *International Journal of Refractory Metals & Hard Materials*, 17, pp. 163-170.
- [4] Kottfer, D. et al. (2013). ‘Investigation of Ti and Cr based PVD coatings deposited onto HSS Co 5 twist drills’, *Applied Surface Science*, 282, pp. 770-776.
- [5] Münz, V.-D. (1986), ‘Titanium aluminum nitride films: A new alternative to TiN coatings’, *Journal of Vacuum Science & Technology A*, 4(6)
- [6] Weichart, J. (2012). ‘Titanium aluminum nitride sputtered by HIPIMS*’, IOP Conference Series Materials Science and Engineering*
- [7] Anders, A. (2010). ‘Deposition rates of high power impulse magnetron sputtering: Physics and economics*’, Journal of Vacuum Science & Technology* A 28, p. 783
- [8] Li, C. (2015). ‘A quantitative approach to analyze carbon emissions of CNC-based machining systems’, *Journal of Intelligent Manufacturing 26*, pp. 911-922

Backup

Cost evaluation if substrate included

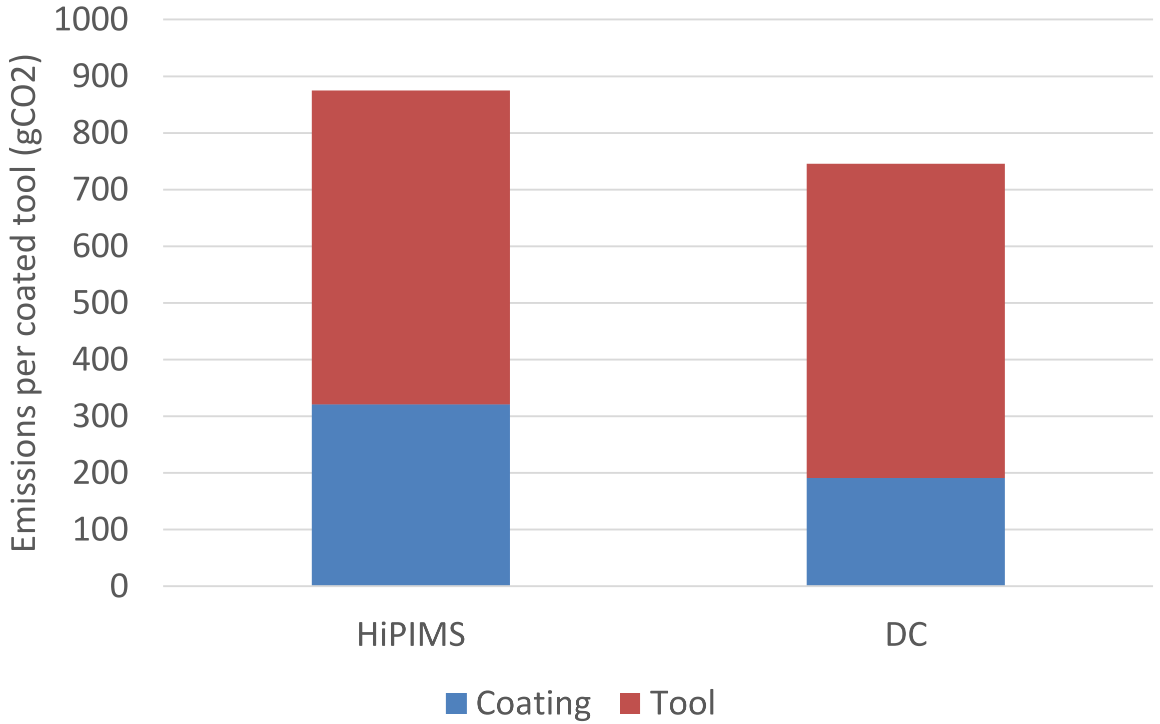
- Avg cost for 8mm HSS milling bits: 6€

➔ Negligible difference for both technologies



Environmental impact with substrate

- Once again, reduced relative difference
- 875 gCO2 vs 745 gCO2



Coatings evaluation conclusions

- For the coating only: 41% increased cost and 68% increase in CO_2 emissions

- With a 50% increase in tool life, increased cost is justifiable (cost/min)

- If substrate is included, results overwhelmingly positive for HiPIMS

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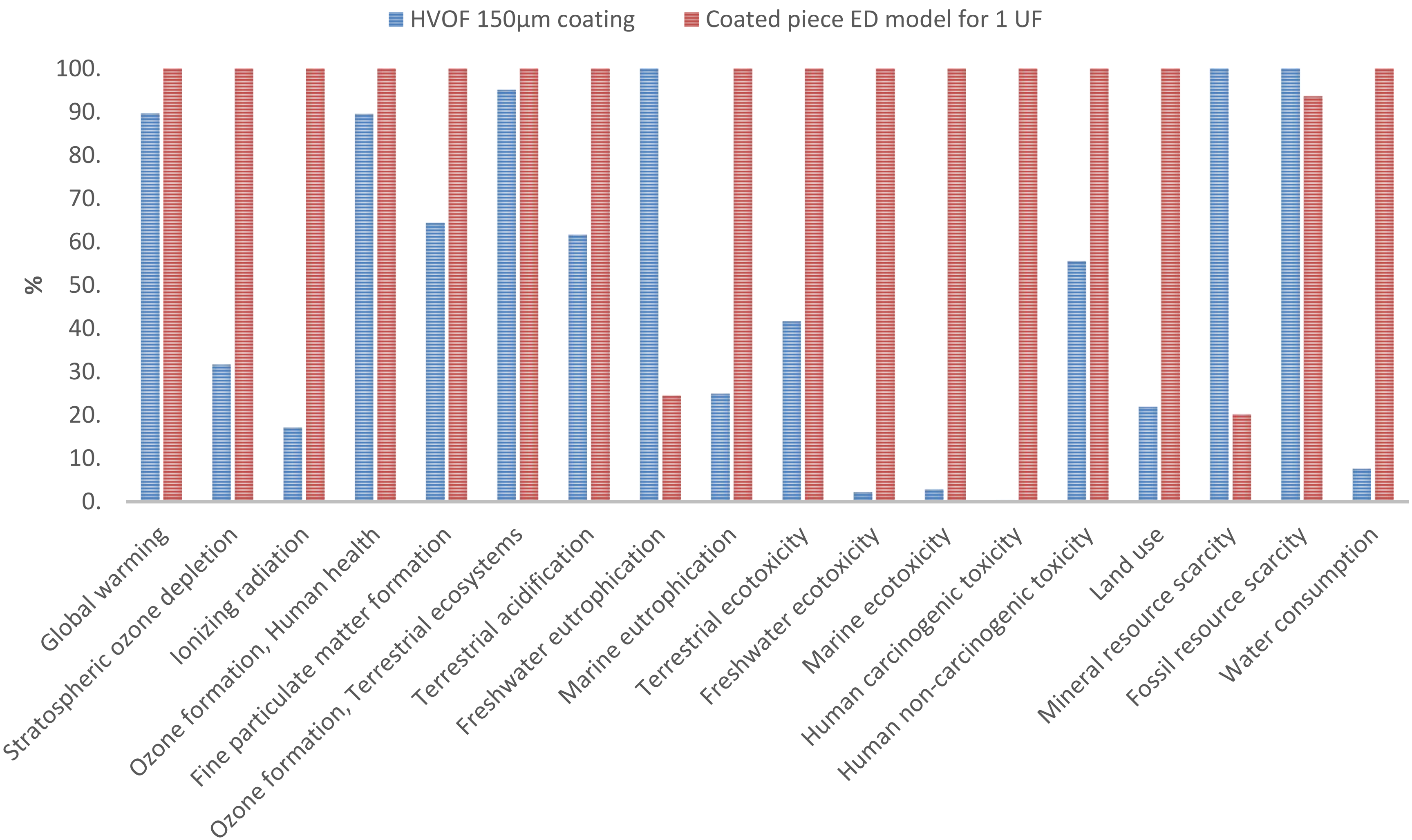
Other results: HVOF

- Evaluation of HVOF as another alternative to chromium electrodeposition

- Results from CRM installation parameters: 370€ (ED) vs 227€ (HVOF) per F.U.
  - Thanks to higher productivity and higher degree of automation

- Also promising due to lower environmental impacts

Other results: HVOF



TiAlN and cutting tools

- TiAlN : improvement of tool properties

- Developped from TiN[5], better corrosion resistance at higher T° (ox. 500-550°C for TiN vs 600°C for TiAlN) ➔ Better performances at high speeds

Table 3. Coating mechanical properties [2]

Type of Coating	Hardness (GPa)	Hardness ($HV_{0.05}$)	Thickness (µm)	Friction Coeficient	Heat Stability (°C)
TiN	23	2350	1 - 4	0.4	500
TiCN	27	2750	1 - 4	0.2	450
CrN	21	2100	1 - 4	0.6	700
TiAlN	32	3300	1 - 4	0.5	600
TiAlCN	29	3000	1 - 4	0.4	500