metamorpha

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Made-to-measure micromachining with laser beams tailored in amplitude and phase

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Deliverable D10.1

Technoeconomic Assessment of laser & machining systems

Technical Coordinator	*Martin Reininghaus*
Organisation	*Fraunhofer ILT*
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Authors	Rodrigo Rivera	ARDITEC
	Jose Gallego	ARDITEC
	Leo Staccioli	ARDITEC
	Diana Torres	ARDITEC
Reviewers	Bruce Napier	Vivid

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Contents

Change register

Version	Date	Authors	Organisation	Changes
DRAFT 0	13-Jan-2024	Rodrigo Rivera	ARDITEC	Draft version
DRAFT 1	24-Jan-2024	Rodrigo Rivera, Jose Gallego, Leo Staccioli and Diana Torres	ARDITEC	Internal Revision 1 Includes comments from PO about METAMORPHA benefits in terms of energy & waste.
DRAFT 2	31-Jan-2024	Rodrigo Rivera, Jose Gallego, Leo Staccioli and Diana Torres	ARDITEC	Internal Revision 2 Includes details about CAPEX / OPEX cost distribution per UC. Inputs from ILT, Philips, tkSE, Ceratizit, Lasea.
DRAFT 3	13-Feb-2024	Rodrigo Rivera, Jose Gallego, Leo Staccioli and Diana Torres	ARDITEC	Internal Revision 3 Includes details and corrections with new energy consumption per UC: New inputs from ILT
DRAFT 4	28-Feb-2024	Rodrigo Rivera, Jose Gallego, Leo Staccioli and Diana Torres	ARDITEC	Internal Revision 4 Includes corrections with new energy consumption per UC: New inputs from ILT, tkSE, Philips
DRAFT 5	07-Mar-2024	Bruce Napier	Vivid	Review; changes requested, especially to analysis of UC-1 and UC-2.
A	20-Mar-2024	Rodrigo Rivera, Jose Gallego, Leo Staccioli and Diana Torres	Vivid	Review; changes requested, include last comments on data and deliverables.

Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the METAMORPHA project: any external source is properly referenced.

Confirmation by Authors:	Rodrigo Rivera	ARDITEC
	Jose Gallego	ARDITEC
	Leo Staccioli	ARDITEC
	Diana Torres	ARDITEC

Abbreviations

CAPEX	Capital expenditure
CuW	Copper tungsten
ECM	Electro chemical machining
EDM	Electrical discharge machining
EDT	Electrical discharge texturing
FTE	Full-time equivalent personnel
LCOP	Level cost of production
OPEX	Operational expenditures
TEA	Techno-economic assessment
UC	User case
WCE	Wet chemical etching

Executive summary

Deliverable 10.1 presents the Techno-Economic Assessment (TEA) of the three processes selected to demonstrate the METAMORPHA laser system. These use-cases (UC) are the following:

- UC-1 PHILIPS: production of one shaving head using electrochemical machining (ECM).
- UC-2 tkSE: production of one roller using electrical discharge texturing (EDT).
- UC-3 CERATIZIT: production of one carbide punch using electrical discharge machining (EDM).

Although the three processes are quite different, the cost drivers observed for all of them are the energy cost and the human power to survey and carry out the activities needed in the production. The latter depends on the complexity of the pieces to be produced, the number of processing steps and the adequacy of machinery.

In order properly to assess the impact of the METAMORPHA laser, all calculations are carried out by integrating the full lifespan of the production unit (*i.e.* including all expenses during its lifetime). Impacts are very different for the three use cases. The EDM to produce the carbide punch (UC-3 CERATIZIT) currently (M18) appears to be the process most benefited by the use of the METAMORPHA laser. Energy savings, efficient use of human resources and limited CAPEX requirements show important reductions on production costs. For the other two UCs, the optimization leads to a shift in the CAPEX/OPEX driving process, in which energy prices become the most impactful variable on the volatility of production. To a lesser extent, the EDT to produce the roller (UC-2 tkSE) and the EDM to produce the punch (UC-3 CERATIZIT) benefit from the laser energy savings.

Structurally, CAPEX is important and locks some optimizations. Expected savings are within a range of 20 % to 30 %, with conservative hypotheses. From other perspectives and besides the economic benefits, replacement of WCE and EDT techniques by the METAMORPHA laser contributes enormously to the reduction of chemical handling, chemical disposal and post-treatment. From a full cycle of production, environmental potential impact due to leaks is improved, as well as all inlets-outlets of materials to the system.

The analysis of the theoretical expectations and the data collected in tests of the METAMORPHA laser shows that the lifespan of the laser system could hinder the savings in any of the processes envisaged in the project, as well as an overconsumption compared to the initial expectations. A full lifecycle of laser could double the CAPEX needed (CAPEX and replacements). It has been observed that up to 10 % of the savings are hindered if the frequency of replacement of laser components increases. In the UCs of Philips and tkSE, current energy consumption data is several times that of conventional technologies, although economics show different impacts on the LCOP.

The commercialisation and business model of the METAMORPHA laser is of paramount importance. Although cash-flow schemes can vary, all partners need to ensure production and limit expenditure. All are experienced in outsourcing, hence also the lease/rental of the laser, or external production could be a pathway of commercialization.

1. Introduction and methodology

This task aims at carrying out the TEA of the current technologies considered in the production process of the partners of the METAMORPHA project, as well as setting the economic drivers that the METAMORPHA laser system should focus on to reach competitiveness. Obviously, the maturity of the laser system is behind the level of maturity of the technologies currently used by the partners in the respective UCs. Hence, this task considers a sensitivity study of the different economic aspects of the laser process to set thresholds of development and key focus areas on the economics, as well as the potential business model.

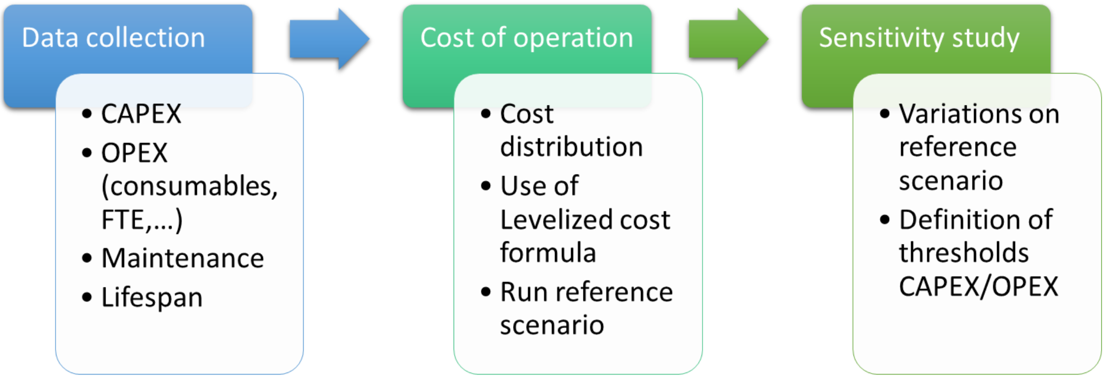

Figure 1. Methodology considered for the TEA of the existing processes and the new laser processing method from METAMORPHA.

The methodology considered in this task is visually represented in **Figure 1** and is described as follows:

- **Data collection**:
  - **CAPEX** – Investment of machinery is obtained from vendors and from the partners in the project. The data gathered provides an average value stated as reference scenario investment. Breakdown of key components of the technology is carried out if relevant. The work limits the information to the machinery and use, rather than the infrastructure needed to install the machinery. This means that the real-state, availability of surface, buildings, taxation of facility *etc.* are not included. The reason for the latter is to render site-to-site comparison homogeneous and to have focus on the technology itself.
  - **OPEX** – this category includes the utilities needed in the process, chemicals needed or disposed of, the manpower necessary for the surveillance and operations, and any other major cost contributor with worth >20 % of the total. Smaller minority costs are not considered in the calculations and become part of the cost value ranges in the sensitivity studies.
  - **Maintenance** – this cost is considered as 3-5 % of CAPEX investment on an annual basis as part of the works needed on preventive maintenance, major overhauls, and scheduled repairs. There is no consideration regarding maintenance due to breakage or failure of the system. This assumption means that the breakage and failure modes are not predictable, are linked to maintenance schedules and use of machinery that can vary from site to site.
  - **Lifespan** – the duration of service of major machinery is considered in the calculations as it results on major replacements during the operating time of the production facility. It is considered that the replacement leads to an investment at the year *t*.

Acknowledgments are given to the partners that contributed during the interviews for data collection and enlightening the processes key drivers. Information in this report is presented mainly in percentages and kept as succinct as possible to protect confidential and competitiveness data.

- **Cost of operation:**

  - **Cost distribution** – based on the information given by partners of the METAMORPHA project, as well as industrial references, the cost breakdown is given per process technology and enables first analysis on key drivers for cost reduction and indicates the potential breakeven for the laser technology compared with the other technologies and potential business models.

  - **Levelized cost of production per item** – the LCOP equation is given below. It has been considered in several TEAs for technologies and improved to consider inputs and outputs of the system, as well as the lifespan of the production facility (*n*), the lifespan of equipment leading to heterogeneous cashflows over the time of the facility[1,2]. In this equation, one assumption embedded is the hours of operation per year. It is considered that a 24/7 production is the reference scenario (8,600 hours per year), while reduction of operating time is considered in the sensitivity study. Another embedded hypothesis is the number of products per year. Although this topic will be covered in more detail in the LCC deliverable, today the production cycle for the laser system from METAMORPHA is considered as equivalent to the existing technologies. This is currently, however, an optimistic assumption that needs further study once the results of the project enable a fair comparison and scale-up of the process. Overnight investments and delivery of the facility (*i.e.* instantaneous implementation) is considered as reference scenarios.

$$LCOP = \frac{\sum_t^n \left[\left(C_{CAPEX,\ t=0} + C_{CAPEX,\ t} + C_{OPEX}\right) \times (1+\tau)^{-t}\right]}{\sum_t^n \left[P_t \times (1+\tau)^{-t}\right]}$$

  C letter indicates cost, while P is related to the production of items per year. The coefficient τ is the actualisation rate considered on the financials and production. The value of this rate is fixed at 8 % as per common practice in industrial projects. The subindex *t* indicates the year concerned in the summatory; it can go to 0 to 20 years. Subindexes in CAPEX at *t=0* and *t* are the initial investment and the cost of replacement after lifespan, respectively.

  - **Reference scenario** – It is the costs assuming a given annual production of items and taking into accounts costs known today as main hypothesis.

- **Sensitivity study:**

  - **Variations on main cost drivers** – these are considered to analyse the balance between CAPEX/OPEX. The latter is of paramount relevance for the laser technology, as it can draw the development roadmap to improve competitiveness and potentially, to redefine the business model for the technology use.

  - **CAPEX/OPEX thresholds** – as part of the assessment of technology competitiveness, the sensitivity study showing shifts in the CAPEX/OPEX ratio indicates the cost driver and key aspects to be focused on for the development of any process.

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The above-mentioned methodology is followed for each of the process techniques used for the preparation of pieces by *Philips*, *tkSE* and *Ceratizit*, as well as for the expected features of the laser system under development in the METAMORPHA project. This report is hence divided into sections per

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[1] Rivera-Tinoco R. Etude technico-économique de la production d'hydrogène à partir de l'électrolyse haute température pour différentes sources d'énergie thermique, March 2009, PhD Thesis, Mines Paristech.

[2] Monzer, D., Rivera-Tinoco, R., Bouallou, C. Investigation of the Techno-Economical Feasibility of the Power-to-Methane Process Based on Molten Carbonate Electrolyzer, Frontiers in Energy Research, 2021.

manufacturing process of the industrial partners in the project, and it concludes with the laser TEA under current maturity status. The work here presented is complementary to the LCC study to be performed. The main target of the current work is the economic assessment and highlighting technical improvements, as well as business models that could render the competitiveness and relevance of the processes highly attractive. The LCC will focus mainly on the return on investment and current competitiveness picture excluding any technical improvement.

2. UC-1 PHILIPS: Electrochemical Machining

2.1. Technical description and economic hypothesis

The manufacturing of the shaving heads consists of many steps (from five to fifteen) according to the requirements of each product. Both ECM and wet chemical etching (WCE) processes need high usage of energy and toxic chemicals, which often require special and onerous handling. In the final electric shaver product, these heads are at the heart of a complex high-speed machine, and they must be manufactured to extremely high precision and tight tolerances. Currently the features of this product necessitate a process chain of a variety of different steps (depending on the product) divided over two different types of process, each of which represents the state-of-the-art in an aspect of manufacturing technology.

Regarding the several steps in the process undertaken by Philips; the ECM is an in-house step with extensive know-how. The etching activities are today externalised and during the interviews it was agreed to take these outsourced activities out of the TEA scope. ECM has been a topic of major interest by several authors, some stating the state-of-the-art [3] and others are even more interesting by highlighting the improvements[4, 5] that can be reached in the domain. Such improvements are beyond the scope of the TEA, although the potential cost reduction is an important point to consider. Despite an extensive search on economic drivers and their real-life implementation, there is no information on main changes leading competitiveness of ECM to better levels. The simplified process scheme is presented in **Figure 2** in which the electrolyte circulation is observed from the container to the constant feed point, connected to the power supply, and generating the machining work to the workpiece also connected to the power supply and closing the circuit.

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[3] Yuan, C.J., Abu Bakar, A.S.H., Roslan, M.N., Weng Cheng, C. Electrochemical machining (ECM) and its recent development. Journal Tribologi 28 (2021) 20-31.

[4] Tang, L., Feng, X., Huang, T.Q., Liu, J., Zhang, J.J., Lei, Q.B., Wang, Z. Research on the combined electrochemical machining and electrical discharge machining technology for closed integer impeller. The International Journal of Advanced Manufacturing Technology (2019) 102:3419–3429.

[5] Swata, M., Rebschläger, A., Trapp, K., Stock, T., Seliger, G., Bähre, D. Investigating the energy consumption of the PECM process for consideration in the selection of manufacturing process chains. Proceedings CIRP 2015.

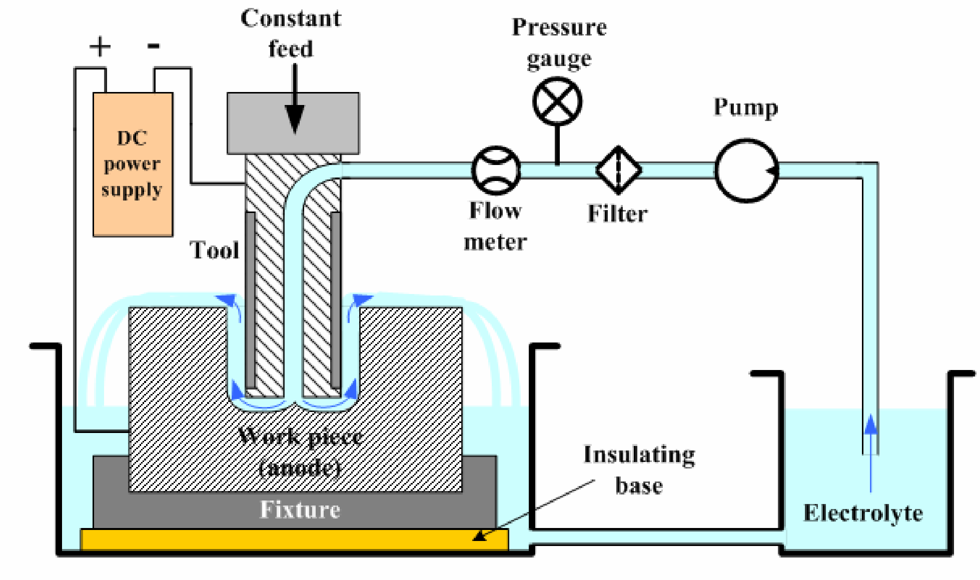

Figure 2. Simplified core processing of ECM[6].

- ***Reference scenario***

    - **CAPEX**

Data collected is highly sensitive and the breakdown is not possible with the level of confidence in hypothesis that could render a cost distribution chart relevant. Hence, the analysis is here based on the general CAPEX figures and the electric consumption, excluding overheads and other cost figures. This is also a benefit since it allows one to compare the technologies independent of the site conditions and company policies. The investment of machinery of ECM is expected to be several M€[7], for a large capacity and with a lifespan that can easily reach the lifespan of a site when the maintenance is property undertaken. Consultation of partners, as well as cost approximate for machines of large capacity were undertaken. In a similar manner to punch production described in Section 4, financial depreciation is carried out in a shorter period of time compared with the lifespan of the machinery itself. In the calculation also in this section, we consider the lifespan of machinery and not the depreciation.

Automation investments are not considered as relevant, as the safety management and other company policies limit the minimum number of Full Time Equivalent personnel (FTEs) needed to properly execute production and other activities.

No other expenses are added, as the installation will require specific buildings that are included in the plant design. The latter is beyond the scope of this study and considering any cost on this topic could lead to misleading conclusions specific to the technologies under study.

    - **OPEX**

Electricity price varies from 80 – 180 €/MWh in a range that is considered adequate for industrial applications. Specific values are confidential and may be linked to the intensity of supply needed for the full facility. The value of 80 € will be considered in the reference scenario as a general figure representative of industrial contracts. To support this choice and the range of electricity cost, an analysis of Eurostat data has been performed. This range is used in the sensitivity studies for all UCs and the METAMORPHA laser. As can be observed in **Figures 3** and **4**, electricity prices in S1-2023 show high values compared with the range, although historical data shows a general average close to 10 €/MWh. The high electricity price

[6] Pandilov, Z. (2018, March). Application of Electro Chemical Machining for materials used in extreme conditions. In IOP Conference Series: Materials Science and Engineering (Vol. 329, No. 1, p. 012014). IOP Publishing.

[7] Industrial interview – Confidential European vendor.

results from the Ukraine war, increase on gas prices and shortage of exports in nuclear power plants in France. From **Figure 4** can be observed that the general trend seems to move towards a range between 0.14 and 0.18 €/kWh, which is exactly within the proposed electricity power range considered in the sensitivity studies.

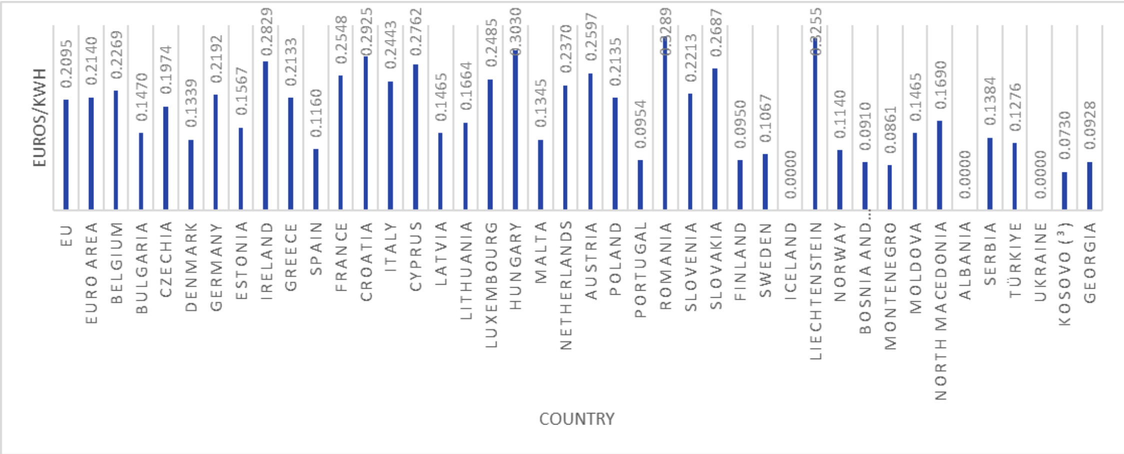

Figure 3. Electricity price for non-household use per country S1-2023 (Source: Eurostat – electricity price statistics).

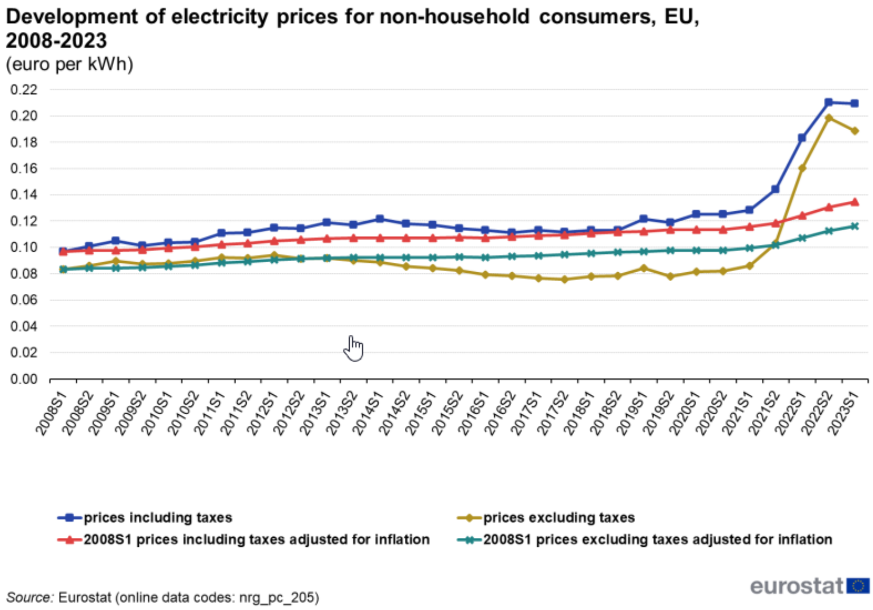

Figure 4. Electricity price for non-household consumers in EU 2008-2023 (Source: Eurostat – electricity price statistics).

Running hours capabilities (availability) require approximately 25 FTE for the surveillance and 24/7 three shifts and for several production lines enabling to meet a production of 30 million pieces. Level of training of personnel increases rapidly when in company and labour market is not under stress regarding specific skills needed. It is considered the potential optimization of FTE usage if the METAMORPHA laser enables elimination of effluents, and other activities requiring large handling of pieces (number of pieces and also materials). In this case, a reduction down to 6 FTE is considered as a hypothesis to analyse the impact of laser use. Although this hypothesis is optimistic, perspectives of changing the current process for one using the METAMORPHA laser needs to be mindful also on the scale of the systems currently in use and the laser to be developed in the project. In a similar manner to the tkSE application described in the next section, experimental results are of paramount relevance to define next steps on competitiveness and automation achievable.

2.2. Results and sensitivity study

In **Figure 5** the share of CAPEX and OPEX for the first year of operations is presented. The high investments initially required dominates the expenses. The results assume an overnight construction of the unit, which is a general assumption enabling the comparison on dilution of investments over time. OPEX only accounts for 9 % of the total.

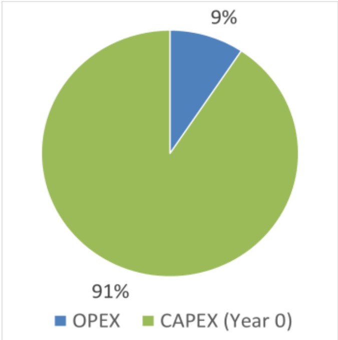

Figure 5. Initial CAPEX and OPEX in year 0 (initial operations) of ECM unit with electricity price of 80 €/MWh.

The counterbalancing of OPEX over CAPEX is observed while assessing the lifespan of the production line. In **Figure 6** are shown the results on the investment and OPEX including the electricity consumption and FTEs considering the full lifespan of 20 years of operation. The Philips process is still highly impacted by the CAPEX. The high lifespan value of machinery avoids visible replacements, and OPEX constitutes slightly higher than half of the total expenses for production of pieces. Among the OPEX, a semi-balanced 50/50 share is observed between electricity consumption and FTEs directly operating the machinery. For the sensitivity study, values of investment and FTE are kept constant, a variation of electricity price from 80 €/MWh to 180 €/MWh is applied. The cost structure and high energy demand leads to an increase of up to 33% on production cost when the electricity price increases.

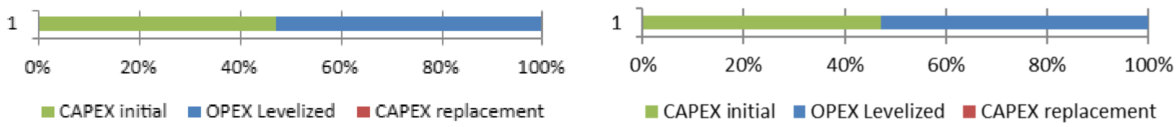

Figure 6. Cost sharing during the lifespan of ECM unit in reference scenario with electricity price of 80 €/MWh (left) and 180 €/MWh (right).

In the Philips use-case, FTE is a major contributor to cost. In **Figure 7**, it is shown the CAPEX-OPEX share considering that the METAMORPHA laser reduces the FTE from 25 to 6 and that electricity needed is also reduced as expected. The impact of electricity price on the CAPEX/OPEX share is negligible. In case of considering an optimistic approach in which the laser lifespan is of 20 years, a drastic production cost reduction is achieved, between 47 % and 52 % depending on the electricity price considered (but <1% variation on the balance CQPEX/OPEX). This highlights that the laser can contribute to the competitiveness of the system, although major improvements on lifespan of lasers, diodes and production cycles are needed. For this sensitivity study and the three UCs, performance of the METAMORPHA laser is considered as in the theoretical performance stated in the proposal. Analysis of recent real data obtained by the partners is presented in the laser Section.

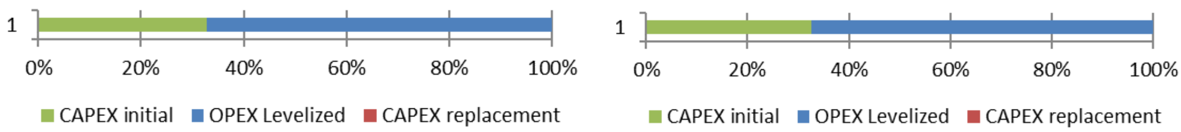

Figure 7. Cost sharing during the lifespan of ECM unit in scenario of laser replacement of FTE with electricity price of 80 euros/MWh (left) and 180 euros/MWh (right).

In a realistic scenario with replacement of components of the laser, FTEs reduced, an investment of 5 M€ of machinery to match the required production level, values of CAPEX-OPEX are calculated. Results are shown in **Figure 8**. Compared with the reference scenario, a cost reduction of 30 % could be reached with METAMORPHA laser, even if replacement of components is needed. The reduction on FTEs drastically reduces the OPEX too, as it can be observed, while CAPEX and replacements would be dominant under this scenario.

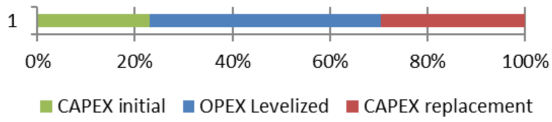

Figure 8. Cost sharing during the lifespan of production unit in scenario in which METAMORPHA laser replaces the current machinery.

An unexplored aspect that could represent an additional revenue stream is the sale of hydrogen produced during process. Depending on the properties of the gaseous stream containing hydrogen, such activity requires a purification and recompression system to be able to use hydrogen in other parts of the site, *e.g.* in vehicle fleets, sale to third parties, *etc*. In general, a final product of compressed hydrogen has a normal value within a range of 4 to 8 €/kg. Any further study on this topic shall include a risk assessment, as the presence of hydrogen could lead to explosive zoning non compatible with the site.

3. UC-2 tkSE: Electrical Discharge Texturing

3.1. Technical description and economic hypothesis

The EDT applied in manufacturing processes is used successfully for large workpieces. However, the existence of chemical waste (toxic gases) and slurries represents a disadvantage of the manufacturing process, among others such as high electrical energy needed and lack of any restructuring process; once rollers become mechanically ground flat, a new EDT process is required. Therefore, this process enlarges waste and cost expenses. Several documents in the public domain refer to the treatment of rolls[8,9] through EDT. In steel production, rollers are used for metal sheet embossing. These rollers have always a surface structure. The surface is important for the end-product and the performance of the rolls. The embossing process generates a lot of wear. Worn rollers must be replaced and subsequently restructured. This is one of the UCs for the METAMORPHA technology. The literature review shows modifications of the operating parameters and chemicals under review, in spite of little public domain information about real goals reached in the industry.

[8] Oberding, I., Adamek, K.K. A New generation of electrical discharge texturing machines.

[9] Evin, E. Electro-discharge texturing of tools surfaces for rolling of steel sheets. Transfer inovacii 32/2015.

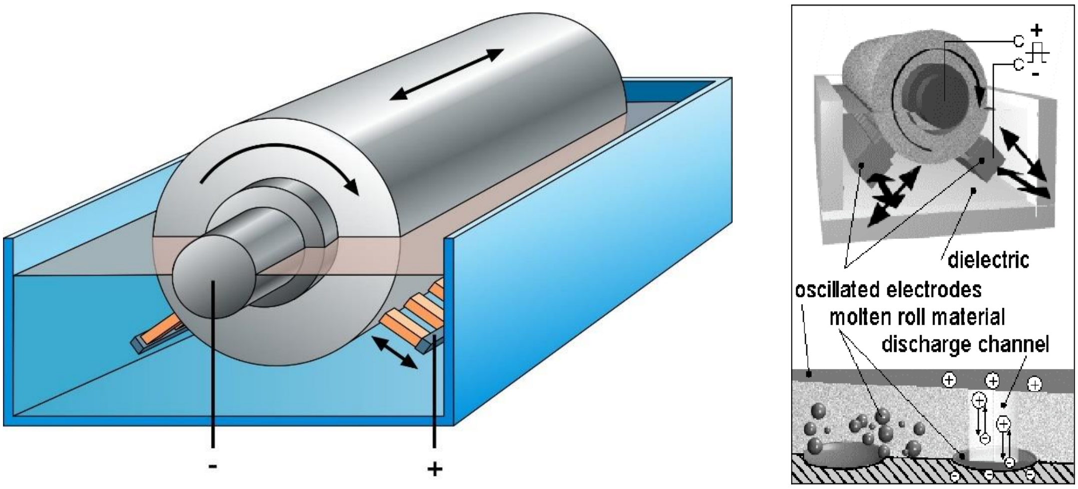

Figure 9. Core processing of roll surface treatment[10,11].

- ***Reference scenario***

    - **CAPEX**

The investment of machinery for the rollers can be divided into two main elements: the surface equipment and the grinding machine. Lifespan of the equipment has proven high longevity and hence, depreciation and amortization reduce any variation if the figure of investment is single or double the value (and not order of magnitude scale). In a similar manner to punch production in the next section, financial depreciation is carried out in a shorter period of time compared with the lifespan of the machinery itself. In these calculations, we consider the lifespan of machinery and not the depreciation.

The CAPEX value remained undisclosed during interviews with partners. Although several attempts to get information from machine vendors were carried out, confidentiality of the project and confidentiality of the cost breakdown of the machinery was not communicated by vendors.

Automation investments are not considered as relevant, as the safety management and other company policies limit the minimum number of FTEs needed to properly execute production and other activities.

No other expenses are added, as the installation will require specific buildings that are included in the plant design. The latter is beyond the scope of this study and considering any cost on this topic could lead to misleading conclusions specific to the technologies under study.

    - **OPEX**

Electricity prices also are considered to vary from 80 – 180 €/MWh in a range that is considered adequate on industrial applications. Specific values are confidential and may be linked to the intensity of supply needed for the full facility. The value of 80 € is considered in the reference scenario.

Running hours capabilities (availability) require approximately 6 FTE for the surveillance and 24/7 three shifts. Level of training of personnel increases rapidly when in company, although finding the first candidates can become a challenge under the current labour market stress. Technical level of employees is today an important requirement. In a job market under stress, specialized profiles are difficult to find,

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[10] https://www.wscgmbh.com/edt.html

[11] Kainz, A., Paesold, D., Riha, G., Krimpelstätter, K., & Zeman, K. (2005, September). Finite Element Modeling of Temper Rolling with Particular Emphasis on Roughness Transfer. In *ABAQUS Austria users conference* (Vol. 27, p. 28).

there is risk of losing employees, and replacement is complicated. The automation is not the only solution, but the METAMORPHA laser could importantly reduce the level of skills at entry needed to the company and relieve part of the pressure on recruitment.

Regarding the perspectives of changing the current process for one using the METAMORPHA laser, it is highly relevant to keep in mind the scale of the systems currently in use and the laser to be developed in the project. The tests to be carried out during the project will shed light on the suitability of the laser system and scale up needed to reach at least the same productivity and production cycle time.

The reference scenario results on a cost distribution as presented in **Figure 10**. This information has been compiled with the partner. A major contribution of the FTE to the total is observed, followed by energy and auxiliary machinery. The cost reduction drivers for this process are mainly on the energy and materials used, accounting that FTEs are needed for safety and policy. On the other hand, a potential change to the METAMORPHA laser needs to show potential reduction of FTE to show a major breakthrough on the production.

3.2. Results and sensitivity study

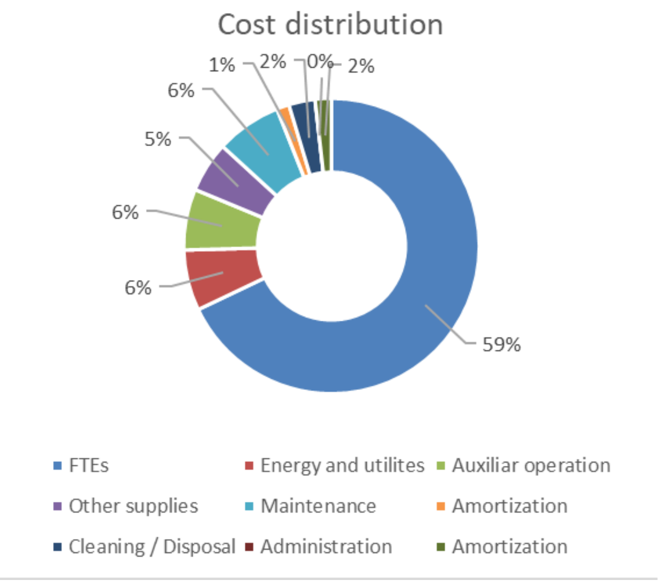

Figure 10. Cost distribution of the EDT production process for rolls.

The merging of FTEs, energy and auxiliary expenses come together in OPEX. In **Figure 11**, the results on the electricity price impact on the share of OPEX and CAPEX are shown. In analogy to the previous section, values of investment and FTE constant, a variation of electricity price from 80 €/MWh to 180 €/MWh is applied. The cost structure and high energy demand leads to an increase of 27 % on production cost when the electricity price increases. The values on the figures here below show a reduction on CAPEX share from approximately 35 % to only 25 %.

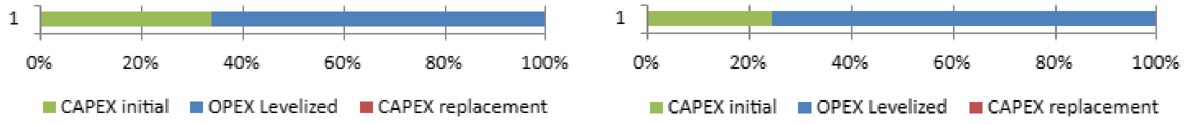

Figure 11. Cost sharing during the lifespan of roll unit in reference scenario with electricity price of 80 €/MWh (left) and 180 €/MWh (right).

As mentioned in the above paragraph, FTE is a major contributor to cost with limited margin of manoeuvre today. **Figure 12** shows the CAPEX-OPEX share considering that the METAMORPHA laser reduces the FTE from 6 to 2 and that electricity needed is also reduced as expected. In this case, it is considered an optimistic approach in which the laser lifespan is 20 years. Such an optimistic assumption leads to a drastic production cost reduction placed between 65 % to 68 % depending on the electricity price considered. This highlights that the laser can contribute to the competitiveness of the system, although major improvements on lifespan of lasers, diodes and production cycles are needed.

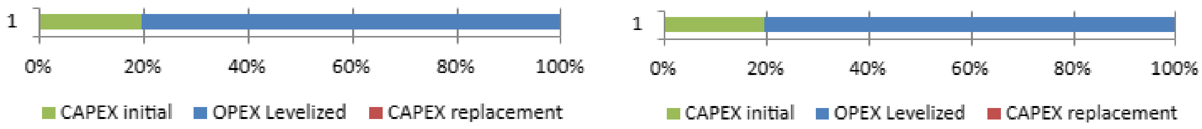

Figure 12. Cost sharing during the lifespan of roll unit in scenario of laser replacement of FTE with electricity price of 80 €/MWh (left) and 180 €/MWh (right).

Considering a realistic scenario with replacement of components of the laser, FTEs reduced from 6 to 2, an investment of 2 M€ of machinery and a cycle-production identical in capabilities to existing machines, values of CAPEX-OPEX are calculated. Results are shown in **Figure 13**. In spite of a shift of CAPEX from initial to replacements, the sum of both is similar to the reference scenario on the surroundings of 35 %. The OPEX hence remains identical in the cost structure. However, the total cost of production of rolls is actually reduced by 56 %. This value does not include all overheads nor any other administrative expenses, as well as infrastructure costs. Hence, the METAMORPHA laser could play a role on the cost reduction of tkSE's activities once the lifetime of lasers, scalability and production cycle are confirmed at least as performant as today's production processes.

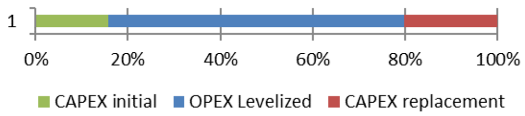

Figure 13. Cost sharing during the lifespan of production unit in scenario in which METAMORPHA laser replaces the current machinery.

4. UC-3 CERATIZIT: Electrical Discharge Machining

4.1. Technical description and economic hypothesis

The production of punches, as well as the surface-shape specifications, have been described in previous reports, the proposal, and the specifications in deliverable D1.1 (schematic representation in **Figure 14**). The punches are made by EDM with previous electrode milling work, and polishing. Additional information on the EDM shows that the techniques keep evolving in the field of machining[12] and advances in different forms of copper tungsten (CuW) electrodes and other materials[13].

[12] Satija., D., Bhute, P., Gohil, V. A study in electrical discharge machining using copper tungsten electrode. Materials today: proceedings. 2023.

[13] Jithin, S., Shetye, S.S., Rodrigues, J.J., Mhetre, K., Mastud, S., Joshi, S. Analysis of electrical discharge textuging using different electrode materials. Advances in Materials and Processing Technologies, 2018.

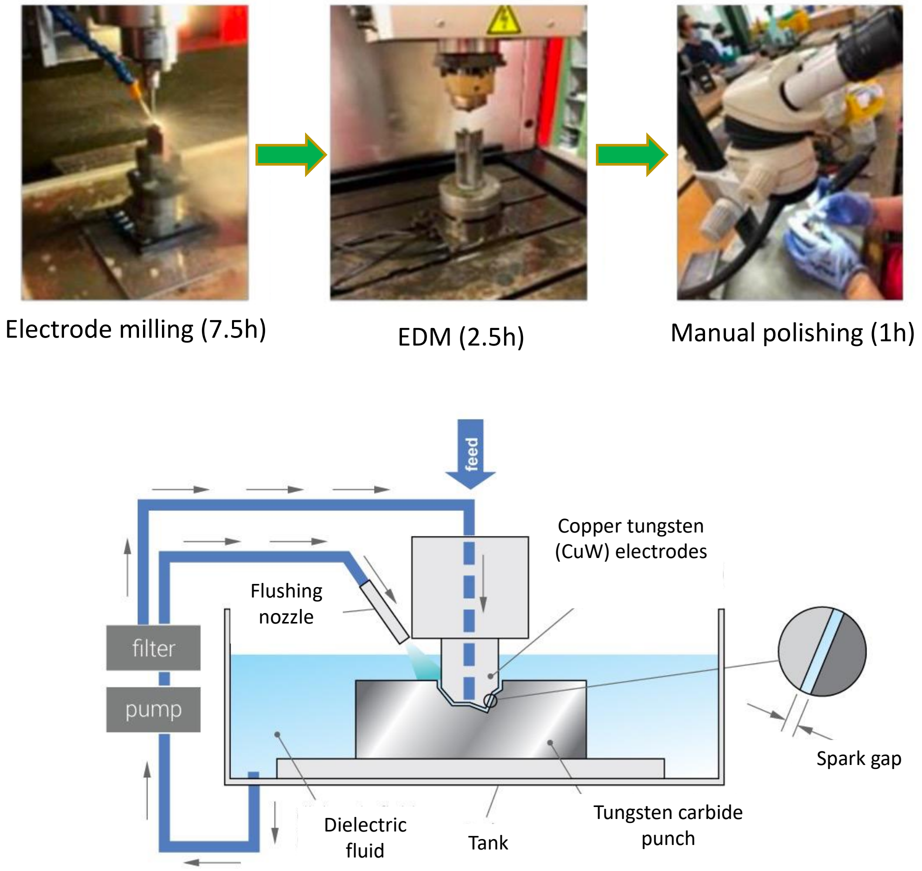

Figure 14. Core processing step for the CuW punches (top) and focus on the EDM (bottom)[14].

The cemented carbide is necessary to make the punch due to its natural extreme hardness. The chain process has three main steps:

1. The electrodes are milled using electrode milling from a carbide blank. The economic and environmental costs of this are high. Each milled punch burns through five CuW electrodes and requires 7.5 h for each punch, and 150 kWh of electrical energy for 1 kg of CuW is required.
2. Definition of the surface structure with EDM. The ablation process is required to meet a 5 µm dimensional tolerance and 5 µm radius for sharp edges. The punch surface is made using a process which requires 50 kWh electrical energy and requires 2.5 h.
3. Manual Polishing. This manual process requires approximately 1 h per punch.

Ceratizit processes annually around 5,000 punches, consisting of 40 % new parts and the rest, 60 %, is the recycling of used punches. Today, the residues are reused or sent to revalorisation chains. According to Zeiler et al. 2021[15], the recycling of copper tungsten and residues shows some limitations. Hence, the laser machining through the METAMORPHA project process could benefit if these non-economical limitations are overcome.

[14] https://www.engineeringclicks.com/electro-discharge-machining-edm/

[15] Zeiler, B., Bartl, A., Schubert, W.D. Recycling of tungsten: Current share, economic limitations, technologies and future potential. International Journal of Refractory Metals and Hard Materials 98 (2021) 105546.

- ***Reference scenario and ranges***

Data collection activities have been focused on major cost contributors as mentioned in the introduction. The following information, similar to the one that will be presented in further sections, remains sensitive. Ranges and percentages will be used to protect confidentiality of information.

- **CAPEX**

The investment of machinery to produce the punches can vary depending on the scope of delivery. The reference case includes production machinery (EDM, polishing and machining) and excludes the possibility to have robots operating the production process and handling the materials. This will be assessed in the sensitivity study below in this section. Main costs considered in the reference scenario are milling and polishing machines, as well as EDM machines.

Financial depreciation is carried out in a shorter period of time compared with the lifespan of the machinery itself. In these calculations, we consider the lifespan of machinery and not the depreciation. The latter is justified by the different rules that can apply under company policy and that can vary.

For the sake of the sensitivity study, the full automation of the material handling and placing in the machines is considered. An investment of 200 k€ is being considered for the purchase of robots and installation. No other expenses are added, as the site modification is not needed in the current partner and, from a general point of view, modification of the site is customer specific and cannot be considered as a solid assumption on costs.

- **OPEX**

Materials are considered as a bulk on spot market price of copper and tungsten.

Electricity prices vary from 80 – 180 €/MWh in a range that is considered adequate on industrial applications, with no electro-intensive purchase agreement, and considering the volatility of prices that the market can show in times of exceptional weather conditions leading to shortage of power supply, excess of demand, and even power plants set in shut-down for safety purposes. The value of 80 € will be the first considered in the reference scenario.

Running hours capabilities (availability) require approximately 10 FTE for the activities of milling cutting, sinking, and polishing. Level of training of personnel increases rapidly when in company, although finding the first candidates can become a challenge under the current labour market stress.

Carbide can vary in composition, and this is relevant to the METAMORPHA process. Although it seems that the use of lasers will not be affected by variations on composition, this question shall remain to be answered during the experimental phase of the project.

Regarding the perspectives of changing the current process for one using the METAMORPHA laser, it is highly relevant to keep in mind that the production in Ceratizit needs to be lean, with preferably a redundancy of machinery to keep operational. Besides the specifications needed for the mechanical aspects, the production cycle time per piece of the laser machinery compared with the current equipment needs to be at least equal to meet production.

4.2. Results and sensitivity study

The reference scenario results on a cost distribution as presented in **Figure 15**. This information has been compiled with the partner and from general data on similar industries using EDM. A major contribution of the FTE to the total is observed, followed by depreciation of machinery. Energy, mainly power, remains in the third place of cost contribution. The cost reduction drivers for this process are mainly on the automation, machinery costs and electricity cost.

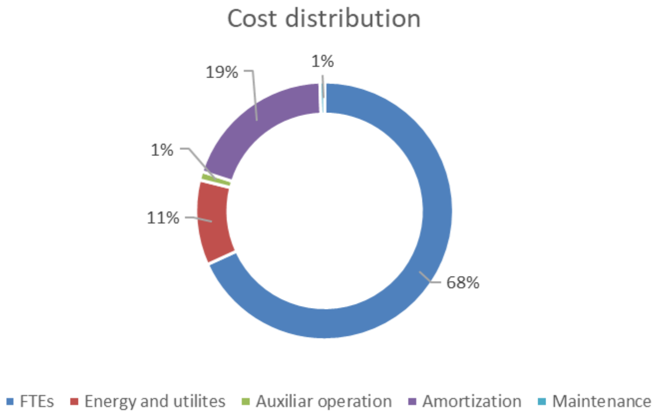

Figure 15. Cost distribution of the EDM punch production process.

The merging of FTEs and energy expenses come together into the OPEX. Expressed in another manner and carrying out a sensitivity study on the cost of electricity, as well as on the impact of automation, the results are presented in the **Figure 16**. By keeping the values of investment and FTE constant, a variation of electricity price from 80 €/MWh to 180 €/MWh leads to an increase of 15.2 % on production cost. Although the doubling of electricity price takes place, the FTE domination on the cost distribution compensates a major volatility on the production cost. This needs to be considered if automation is envisaged. Expenses on electricity, as a volatile part of the OPEX, will become more relevant and production costs will be affected.

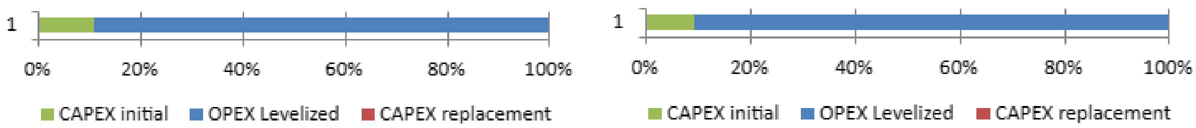

Figure 16. Cost sharing during the lifespan of production unit in reference scenario with electricity price of 80 €/MWh (left) and 180 €/MWh (right).

As mentioned in the above paragraph, FTE as a major contributor to cost can be optimized by automation. An implementation of robots with the CAPEX needed and some major replacement of components during the lifetime of the production unit lead to the results presented in **Figure 17**. Compared to the reference case, the OPEX share is decreased. In relative values, it seems that the CAPEX has almost doubled. However, in real values, the production cost per unitary piece is reduced from 23 % to 38 %, at 180 and 80 €/MWh respectively. The results are logical, as the lower the electricity price, the higher the reduction of production costs: automation is considered to reduce the FTE to only 3 instead of 10. Other point of view is that production cycles are reduced, and FTE remains high. Then, productivity increases with limit impact on CAPEX depreciation, as the process is OPEX dominated.

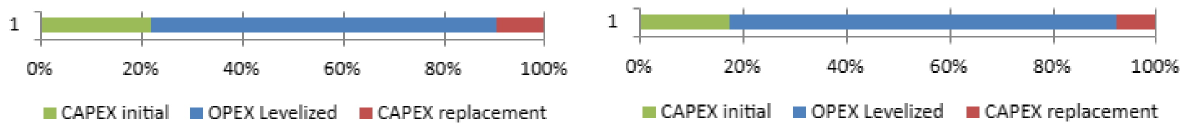

Figure 17. Cost sharing during the lifespan of production unit in scenario of full automation with electricity price of 80 €/MWh (left) and 180 €/MWh (right).

To conclude the analysis of the Ceratizit process, the impact of the METAMORPHA laser on the production of carbide punches is estimated. The laser machines replacing the current equipment show a different cost breakdown and need replacement of pieces (e.g. diodes) during their lifetimes. For an identical production cycle time, the METAMORPHA laser will enable a reduction of costs and reshuffle the cost drivers of the carbide punches: in **Figure 18**, the cost distribution CAPEX, OPEX and replacement is shown. Initial CAPEX and replacement increase compared to the reference scenario. OPEX is mainly driven by FTE and electricity prices have limited impact. The reason for showing only one figure without the variation of electricity price is that the variation of results between 80 and 180 €/MWh is negligible.

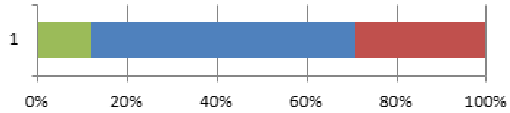

Figure 18. Cost sharing during the lifespan of production unit in scenario in which METAMORPHA laser replaces the current machinery.

The results are aligned and even beyond the expected improvements mentioned in the literature. Two documents have been considered to benchmark the state-of-the-art on improvements in the EDM technologies[16] in spite of a long-term expectation to reach the target[17]. The laser used in the case of Ceratizit production could lead to a 47 % cost reduction per piece if the production time cycle is the same or shorter than current production.

5. Novel laser machining - METAMORPHA

The METAMORPHA laser machinery, besides reaching the specifications regarding mechanical machining of the pieces here considered, requires certain improvements from an economical point of view.

- **CAPEX**

The data collected from partners and literature show three main drivers, which are: the laser sources, the beam shaping module and the machine itself, with the respective balance of plant and hardware. Information about additional first investments are on the controls, the drivers and potential algorithm adaptation, besides an installation period of a couple of days to enable the machine to start operations (and calibration). **Figure 19** shows a preliminary expenses pie chart that has a major impact on the business model considered for the laser.

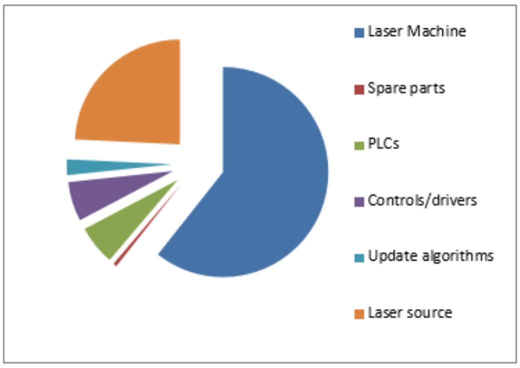

Figure 19. CAPEX cost distribution of the METAMORPHA laser.

The use of a business model based on selling machinery can be interesting from a cash-flow point of view, while the earnings could be limited as mainly spare parts and software updates would be generating revenue on a constant basis. This cost breakdown is typical of a system that could be rented or under a lease use (or pay for what is produced only). Moreover, data to cloud, remote operation and other services

[16] Zhang, Z., Yu, H., Zhang, Y., Yang, K., Li, W., Chen, Z., Zhang, G. Analysis and optimization of process energy consumption and environmental impact in electrical discharge machining of titanium superalloys. Journal of Cleaner Production, 2018.

[17] Uhlmann, E., Piltz, S., Schauer, K. Micro milling of sintered tungsten-copper composite materials. Journal of materials processing Technology. 2005.

can be a potential source of benefit for customers using the METAMORPHA laser, as well as a business opportunity for the partners exploiting the technology.

From information presented in **Figures 20** and **21** the following can be commented:

- Pressure on demand for diodes and laser sources will remain high beyond 2025. The market expansion for applications, including material processing in dark blue, has been already forecast since 2019 in reports of market trends. This means that the supply chain will remain under stress and fabrication of any machinery will need stock management for meeting deliverables.

- The reduction of cost per power available from diode lasers has exponentially decreased over the last 20 years. This means that the diodes themselves will not be the cost reduction driver, but the machinery and assembly will be. Moreover, the outstanding cost reduction of costs/watt is reaching already a plateau. This means that for any reduction of cost, production of diodes, experience, improvements, etc will only be observed in several years from now (learning curve theory).

- From the cost breakdown and cooling capabilities, new legislation makes use of refrigerants more and more stringent[18]. Although the temperature control in the laser machines will remain in mild temperatures close to atmospheric, cooling units may vary in price and refrigerants in the coming years. This will lead to cost increases on the balance of plant that is actually one of the dominant CAPEX aspects.

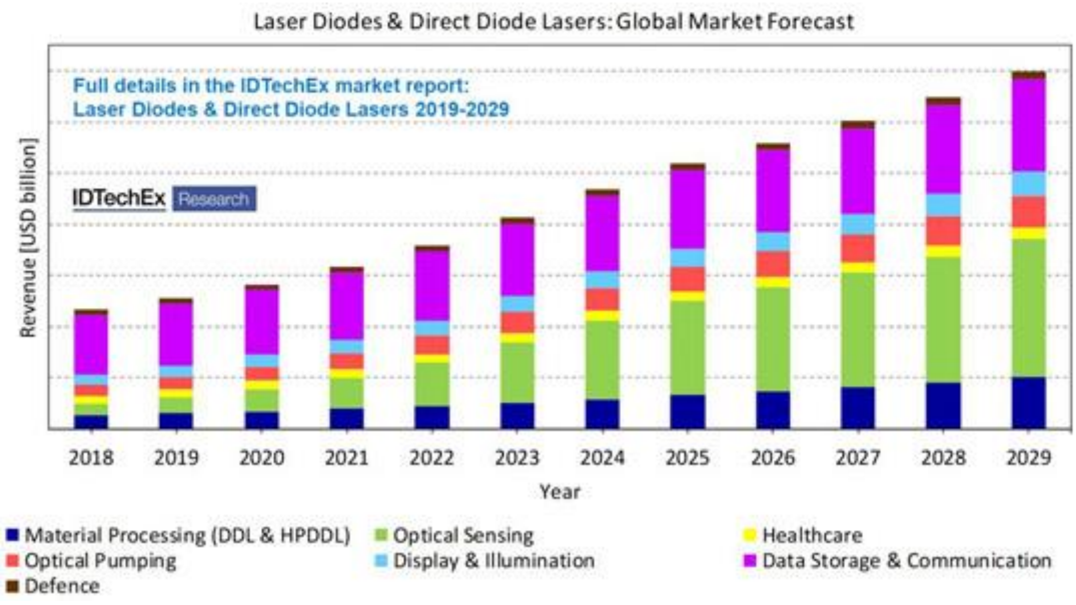

Figure 20. Forecast of Evolution of laser markets per use[19].

[18] EU legislation to control F-gases.

[19] Semiconductor today: Laser diode and direct-diode laser market to grow to $13.985bn by 2029.

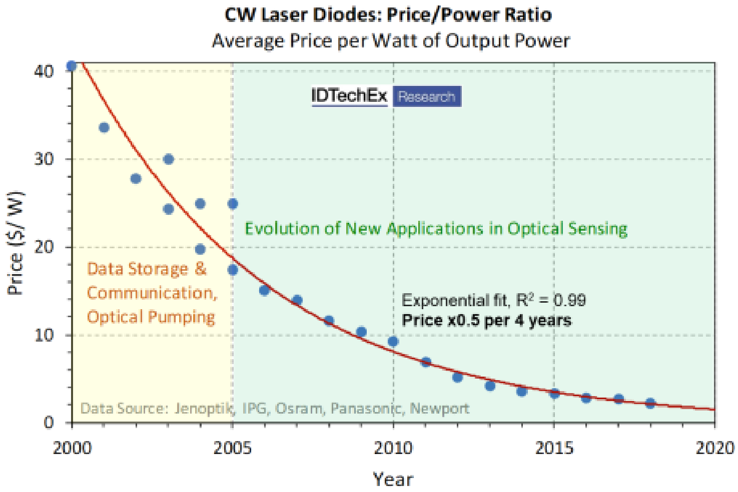

Figure 21. Historical price per power decrease on laser diodes[20].

An additional point that can be explored to reduce the price of machinery and to develop the productivity per system, is the use of multi-head systems. From a mechanical point of view, this is a major advantage for economies of scale and handling in a central point for maintenance. The critical point is the capacity of operating in 4D with simultaneous lasers and the machining needed.

- **OPEX**

From an OPEX general point of view for the METAMORPHA laser, the most important is the low use of energy in the laser and the cooling unit keeping the temperature of the laser within a range of 20°C to 25°C. The chilling or heat removal from the laser represents 80 % to 90 % of the energy losses.

The laser lifespan observed in very favorable conditions is ~30,000 h (98 % availability). In general, based on experience in other industries, 10,000 h have been observed and this is the number of hours considered in the previous chapters regarding replacement of diodes and sources.

Electronics and axes components are the most complicated today in the supply chain, as it is still under confirmed stress since Covid-19 (USA, NL, UK). Standardization of components and use of mass produced items is in progress. However, the maturity of the machine to be developed in the project does not allow for a formal stock or supply strategy (this will be in industrialization).

Feedback from the development work packages and the experiments carried out is needed in order to further refine the economics of the METAMORPHA laser and its impact on the processes of the partners contributing to this task.

Control of lasers and optimization by means of AI, cloud and any other centralized system could be a solution to reduce CAPEX onsite, while benefitting from centralized data treatment and computing power. This is particularly interesting from a CAPEX and OPEX point of view (see **Figure 22**):

- Computing power in the cloud will remove hardware in the system and will have better pricing in cloud services. CAPEX reduction, even minor, represents a competitive advantage as 86 % of computing costs are driven by CAPEX and themselves are about a quarter of the total of the laser machine.
- Algorithms can get more and more robust without intervention on site to refine modelling and controls. Cloud computing under a fleet management approach can benefit the machine learning data access, as well as the velocity of improvements.

[20] IDTechEx Reports: Laser diodes and machines

- Remote access to data of machines and centralized treatment can offer major economies-of-scale, but it opens the question on how to deal with confidentiality, safe connection to machines, security protocols, speed of data transfer, size of files and management.
- Removing control and AI/cloud treatment can also benefit to precalibration actions, fostering the automation of machining.
  - ♦ Image recognition from CAD to piece and robot adjustment of lasers
  - ♦ Control and signals indicating need for maintenance.

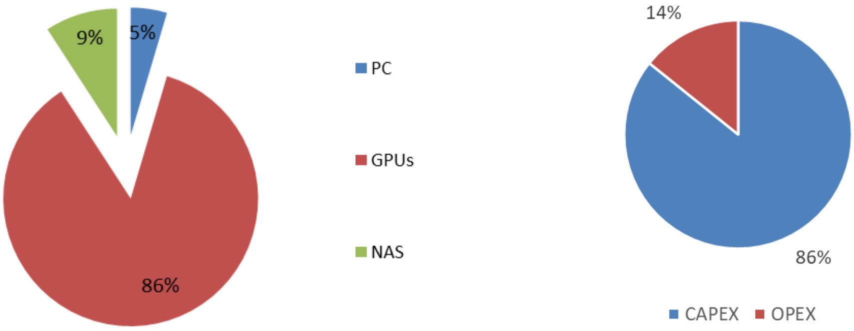

Figure 22. CAPEX breakdown (left) and CAPEX/OPEX share (right) on Computing+Algorithm activities.

As can be deducted in the lines here above, it is of paramount relevance to the teams of AI/cloud to consider the optimized approach of algorithms and streamlining the data transfer to and from the cloud to laser systems. This could have a major impact on the competitiveness and robustness of solutions implemented in the project.

UC1 - Philips

The expected results on energy consumption are slightly lower than the baseline of energy consumption of the ECM processing step showing 0.088 kWh. The project team will work to reach this energy reduction based on preliminary early results. By considering the cost CAPEX/OPEX ratio initially observed, about 50% of the ECM process is driven by CAPEX. The replacement of ECM by laser leads to a lesser CAPEX with higher running costs.

Improvements to consider in the coming months to reduce energy consumption should focus on the machining algorithm can be an important option to do both, a reduction in the energy consumption and the acceleration of the machining process per piece. Besides the observed economic trends, the laser is showing a total reduction of waste effluents.

UC2 - tkSE

Theoretical calculations show values that the METAMORPHA Laser process has the potential to reduce by 8-fold the energy consumption and processing times of hours, instead of days. In a similar manner to the UC-1, the energy consumption values obtained in the preliminary tests indicates the need to carry out further optimizations of the lasers. The case of UC-2 is slightly more sensitive to energy increases and productivity. Long processing time could lead to LCOP increase of several times. As in the case of UC-1, the waste generated in the conventional process is totally eliminated by the METAMORPHA Laser process. In general, the state-of-the-art on waste management can be sometimes a source of revenue in some recycling systems[21] and new developments to separate fluid from, solid phases[22]. Besides the grinding sludge, the fluid management of the EDT is eliminated.

UC3 - CERATIZIT

In this last UC, the economics are playing in favor of the laser. Test results show close to 10× energy reduction. Although the expectations are higher, this value is extremely encouraging and can be improved further by optimizing the algorithms controlling the machining. Considering the cost breakdown of the Ceratizit process, the result is already very positive, and **Figure 23** intends only to assess the impact of potential premature decrease of efficiency of the lasers. Another major advantage observed in the preliminary input of the METAMORPHA laser process is the increase of productivity. The time is reduced by 4×, from 10 hours to 2.6 hours. This means that productivity and automation have the potential to reduce costs by at least half costs related to FTEs and processing (materials remain the bottom cost line).

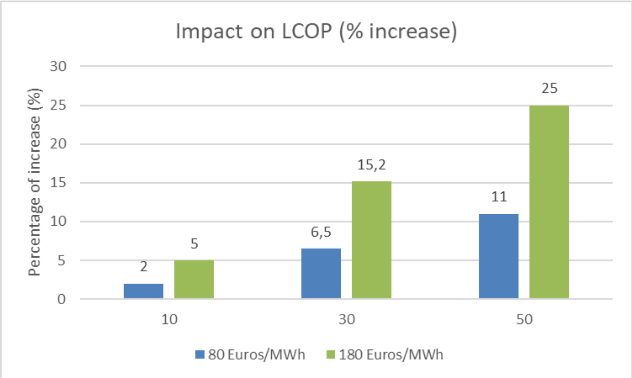

Figure 23. Variation of LCOP depending on the increase (times) of OPEX.

6. Conclusion

Different scenarios have been considered in this study with respect to a variety of factors such as production cycle time, investment in automation of material, machinery costs (including maintenance) and electricity range prices among others. FTE expenses, investment and energy loss will be significantly reduced, as well as strengthening the cooling process, leading directly to lessen the cost of production (proportionally related by the electricity price at the moment), and the consumption of energy. Major improvements on the lifespan of the lasers, diodes and production cycles will need to be held in order to enhance competitiveness of METAMORPHA laser process. Experimental results are expected to confirm this positive trend and to back-up the competitiveness trends indicated in the chapters of this report.

The UCs benefit largely from the METAMORPHA laser process in different ways.

- Ceratizit can have major impact and cost reductions in the production lines, if also accompanied by automation of lines.
- In the cases of Phillips and tkSE, announced potential energy savings is at least 8 fold lower than existing energy consumption. Although automation remains moderate, more

[21] Recovery of grinding sludge https://recyclinginside.com/recycling-technology/volume-reduction-technology/millions-of-liters-of-oil-recycled-from-grinding-sludge/

[22] Hankel, J., Jäger, S., Weber, S. Development of a recycling strategy for grinding sludge using supersolidus liquid phase sintering. Journal of Cleaner Production, 2020, 263-121501.

automation and the savings on handling materials, chemicals, risks to environment and other costly actions with potential impact on safety are very relevant.

- In all of the User Cases, the METAMORPHA laser process can benefit greatly from data handling through the cloud as Machine Learning, as well as AI algorithms can benefit from fleet management data to improve image recognition, machining procedures and storage of data. This not only benefits the algorithms and optimization of coding, but reduces the hardware needed in the machines. It is observed that efforts on reducing CAPEX of systems by multi-laser machines and with fewer GPUs will transfer the CAPEX to OPEX, render the entry pricing and services more affordable to users in the consortium, and more extensive, to future users.

The latter leads to lower CAPEX, hence benefits the competitiveness of the machines. Other actions on CAPEX are suggested in the previous section. Considering the stress on laser demand coming in the next years, a full supply chain and storage management system is required to have competitive hardware (laser machines and respective Balance of plant), as well as data management to improve efficiency and implementation.

KPI	UC -1 Philips	METAMORPHA Laser	UC -2 Thyssenkrup	METAMORPHA Laser	UC -3 Ceratizit	METAMORPHA Laser
Energy consumption (expected results)	0,101 kWh	0,09 kWh	46 + 36 kWh/m²	10 kWh/m²	70 kWh	8,5 kWh
Waste	Chemicals, gas emisions	-	Grinding sludge, chemicals	-	Polishing material, dust, grinding materials	-
Production time expected	<9min	<9 min	hours	3,6 hours/m²	10 h	2,4 h
CAPEX driven	Yes	No	Yes	No	No	No
OPEX driven	No	Yes	No	Yes	Yes	Yes
Cost compared to current situation		Higher		Higher		Lower

From the summary table, main take-aways are:

- UC-1 Philips shows an important environmental improvement by reducing all chemicals and gases. Although processing time is still too high and reduces productivity, there is still room of optimization of algorithms and sequencing of machining to reduce the energy consumption and increase production time. The fact of having a process CAPEX driven to OPEX driven makes that the impact on total production cost is limited. Algorithm optimization and further research to be undertaken will enable to decrease the energy consumption towards the targeted value.
- UC-2 tkSE was taken from a simple single spot process. The process may highly benefit also from a waste management perspective. Theoretical energy and production time remain the target to be accomplished in the coming months. Defining sequencing of machining, complexity of shapes/geometries and fostering the Machine Learning actions, energy and production time can be reduced. Based on the last results, partners in the consortium are already working on steps to maximize the productivity. Once the optical stamping set-up is established, the process will be more efficient and faster. For instance, it could be possible to stamp up to three (3) elementary cells parallelly with a repetition rate of 100 kHz and 100 pulses for the target depth, the laser should take approximately 3.6 h per m² (without mechanical axial movement).
- UC-3 Ceratizit. As a non-CAPEX driven process, the operations of METAMORPHA laser process confirm the trend on high competitiveness and productivity improvements compared to current processing steps. The current results of the laser performance already show major impact on energy savings and productivity.

The information presented here is complementary and interconnected to the task T10.3 “Economic impacts evaluation” and the deliverable D10.2 “Final sustainability and standards report on LCC” which will be submitted in M48. On the latter mentioned deliverable, the current competitiveness snapshot will be calculated and information about return on investment, internal rate of return and periods of depreciation. There are still several tests planned by the partners of METAMORPHA that could reduce the costs of production and fine tune the production time and energy consumption, in particular for the cases of UC-1 Philips and UC-2 tkSE. It is also important to highlight that results from the METAMORPHA project may lead to a certain suitability of machining by these lasers and not the full pallet expected in all user cases and pieces.