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Energy measurements and LCA of remanufactured automotive steel sheets

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Abstract. New paradigms based on Circular Economy (CE) principles are needed for boosting the ecological transition and improving the energy and material efficiency. In this paper, a novel remanufacturing process chain for End-of-Life (EoL) automotive panels is first presented. The core of the recycling strategy is the reshaping of curved EoL automotive sheets through flattening by means of a hydraulic press. Flattening experiments together with press power consumption measurements have been performed on thin steel parts. While the experimental procedure demonstrated the technical feasibility of flattening "small-scale" steel parts, a more complete analysis on environmental sustainability was required. For this purpose, a Life Cycle Assessment (LCA) of the remanufacturing process chain proposed was set up. The results of the study demonstrated that flattening is a viable solution for reshaping EoL automotive panels, and that, for one kg of reshaped steel, approximately 2.2 kg CO_2 and 24 MJ could be saved.

Introduction

The production of metals accounts for about 8% of total global energy consumption [1]. Concerning the steel industry, the production of 1 ton of solid steel corresponds to a primary energy demand of 23.2 GJ [2]. Cullen et al. (2012) stated that the global steel demand is expected to increase tremendously [3].

Steel production and recycling is also strongly linked to the market dynamics, geopolitical instabilities or pandemic events. Those two factors can have a profound impact on the steel flow, availability and price [4-5]. Considering the presented issues, it is crucial for engineers and researchers to examine the entire process chain of sheet metals, including recycling, looking for potential resource efficiency improvements [6].

Recycling proved to have direct positive, demonstrating to be less energy demanding than raw material extraction and production [7-8].

Considering the recycling of End-of-Life Vehicle (ELV), recyclers use efficient processes to recover valuable materials like steel and aluminum alloys [9]. The quantity of metal recycled from end-of-life vehicles is a result of the technology available and the extent to which the technology is used in the scrap processing industry [10].

The steel production by EAF represents worldwide 28% of the total and reaches 46% in Europe (2017, [11]). EAF plants are mainly fed by metal scraps, thus being much less environmentally impacting than blast furnaces. Nevertheless, EAF has relevant impact on the environment, while approximately the half of the energy input is wasted during the process [12].

Considering the aspects aforementioned, there is the incumbent need of efficient methodologies, such as circular economy paradigms, to improve the material efficiency of EoL steel sheets [3]. Increasing the material efficiency can be achieved by six strategies: Reduce, Reuse, Repair, Remanufacture, Recycle, and Recover [13]. Applying these strategies is not always straightforward because of practical problems: Cooper and Gutowski [14] listed the enablers and barriers related to the improvement of material efficiency. Political actions, legislations and the collaboration with associations or national institutions can be a driver for implementing sustainable solutions [15].

The the general opinion of the scientific community is that there is margin to find alternatives, whenever possible, to replace the conventional remelting of metal panels [16-17]. These practices can be divided mainly in two approaches: solid state recycling and direct remanufacturing for reuse of metal panels.

Solid state recycling involves the formation of a billet starting from shredded particles and/or powders. Several routes are possible, such as hot compression [18], hot rolling [19], cold/hot extrusion of chips, Spark Plasma Sintering (SPS) with compaction and extrusion [20], friction consolidation through a rotative die plunge [21], Submerged Arc Welding (SAW) of metal chips and metal waste [22]. Although technically feasible, in solid-state recycling, the material must be available in form of small pieces (or powder), requiring a shredding stage in the product’s life cycle.

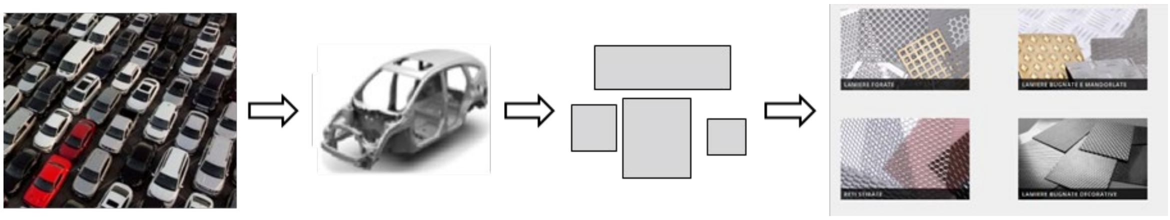
Reshaping strategies instead are meant to directly utilize a metal panel avoiding shredding and compaction and providing new shape or directly performing new stamping operations on it. For example, Ali et al. [23] proposed an innovative recovering strategy for large industrial scrap from the automobile industry producing metal facade systems for buildings. Other researchers such as Ingarao and Takano employed incremental forming to reshape aluminum alloy panels [1,24]. The proposed routines highlight the capability of reshaping panels, but the application of incremental forming could be potentially limited to small batches due to the need of programming the tool path case by case. Two other interesting studies were conducted by Abdullah [25] and Haase [26]. Abdullah developed a methodology for reusing EoL car bodies into mesh steel defining five sustainability indexes. Haase designed a lifecycle based on pre-used material (car roof) to obtain by stamping operations a brake disk cover part.

The present study presents first the main results of remanufacturing tests of thin steel parts through cold and warm flattening with a hydraulic press. The measurements of the press energy consumed during these tests are presented. The measurements were needed to setup a Life Cycle Assessment (LCA) of the remanufacturing routine through the SimaPro software package and to understand the different contributions of power consumption during the flattening cycle. The performed analysis showed the promising results obtained by flattening thin steel parts and the environmental benefits associated with it.

Flattening as a Viable Solution for Remanufacturing Eol Sheet Metals

In the framework of circular economy and environmental sustainability, this paper presents a novel remanufacturing cycle for car body panels. The concept proposed is to exploit EoL car bodies (preferably large panels) to produce metal sheets reusable for a new life, as described in Fig. 1. The largest panels, having often a given curvature, should be first trimmed, then flattened and eventually reshaped. A potential part to be reshaped from an EoL car is the car roof shown in Fig. 2.

The flattening process can be performed through a hydraulic press, whose tools are simply hard steel plates able to flatten car bodies of different models in a “short” time. The tooling costs are expected to be reduced due to the simple geometry. Flattened parts, once characterized, can be then used as regenerated blanks for subsequent forming or shearing applications. The proposed cycle clearly produces blanks which are not uniform and perfect, which might have some defects, but final imperfections are not necessarily a problem for some final intended uses and applications [27].



Dismissed fleet cars. *Dismantled EoL car.* *Warehouse of classified and characterized flat or corrugated sheets.* *Regenerated blank.*

Fig. 1. Remanufacturing framework for car bodies.

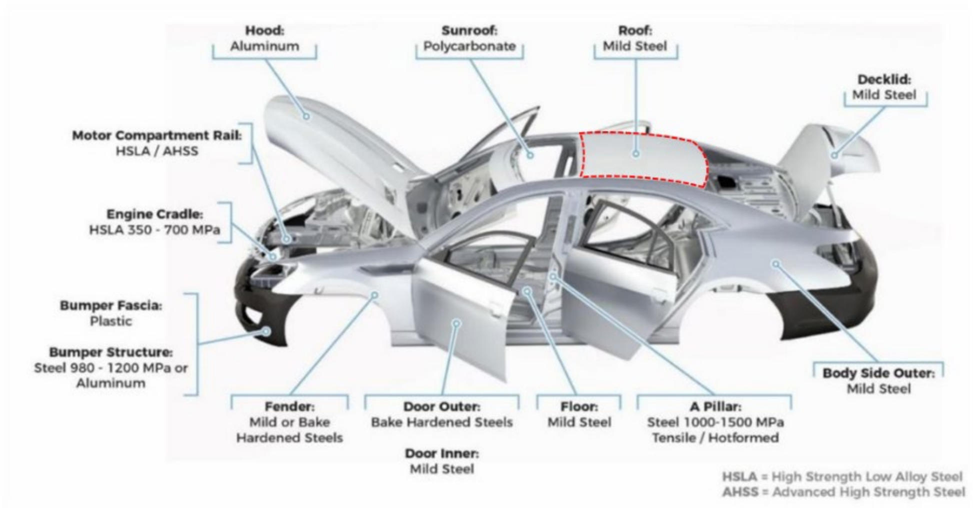
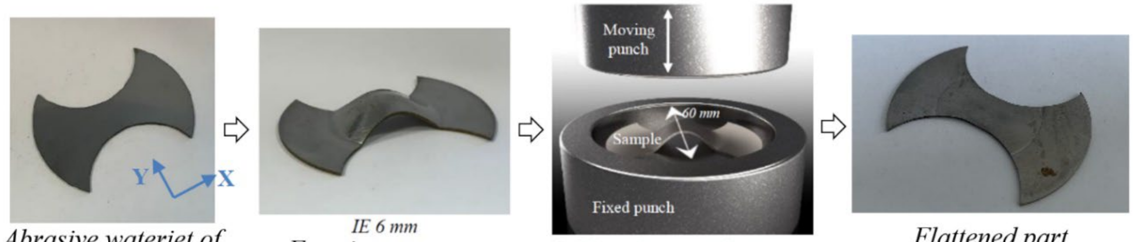


Fig. 2. Example of first use component (car roof) [28].

Flattening Experiments and Press Power Consumption Measurements

Considering the framework presented in the previous Section, tests were carried out to understand the feasibility of flattening curved parts and to test the influence of the main process parameters on the results of the flattening process. The press used for flattening experiments is a SACMI PH150. It is a double effect numerically controlled hydraulic press with maximum tonnage of 150 ton and heated dies (up to 600°C). The control system of the machine uses a pressure sensor applied to the hydraulic cylinder that is governing the press slide, which is in turn used to regulate the applied load. One linear encoder is mounted on the press slide and one on the extracting cylinder to control the vertical position of the punch. Pressure and position can be recorded as analogic signal by an external controller.

The parts to be flattened were obtained by shaping in controlled and repeatable conditions 0.8 mm thick virgin DC 04 sheets (EN 10130, 2006). The shaping process was performed with an Erichsen test machine imposing up to Erichsen Index (EI) equal to 6 mm. The flattening cycle, summarized in Fig. 3, is a sequence of different operations. First, the moving punch (represented in Fig. 3) moves fast (>10 mm/s) approaching the sample. Then, when the punch is close to the sample, the velocity of the piston is reduced to 1 mm/s and continued until the tonnage reaches a predefined set level. The vertical displacement continues at constant velocity until the press tonnage exceeds the set level, called dwell force (F_d). This force is reached when the sample is almost completely flattened. When the tonnage has reached the set value, the piston is held in position for a given dwell time (τ). After the dwell time, the tonnage is released, and the piston moves up.



Abrasive waterjet of DC 04 steel, 0.8 mm

IE 6 mm
Forming process through Erichsen testing machine

Cold and warm flattening through hydraulic press

Flattened part

Fig. 3. Experimental procedure followed: shaping thin steel parts and then flattening through hydraulic press.

The main process parameters varied in the tests were: the pre-forming index *EI* (mm), the dwelling time τ (s), the punch and die temperatures T_T (°C), the dwelling force F_d (tons). The experiments showed that the best quality of the flattened part is achieved by warm flattening with short dwell time. Similar results can be achieved also by cold flattening. In general, flattening can be considered as a promising and effective process for recovering EoL panels.

The press power consumption has been measured under different conditions: during idle time, during flattening (considering different tool temperatures) and during the heating phase of the dies (with pump for oil recirculation turned off). Indeed, quantifying the energetic inputs of remanufacturing is fundamental to assess the environmental sustainability of the process and to understand the benefits with respect to conventional recycling by melting.

The press power consumed has been measured through LEM sensors, which can capture the current and voltage of the three phases. From those values, it is possible to compute the electric power absorbed by the machine. The sensors were mounted around the cables of the main power supply unit of the press, thus detecting all possible contributions of press energy consumption.

Results of the Press Power Measurements

The main results of the press power measurements are summarized in Table 1, while Fig. 4 shows the power consumed during one flattening cycle performed at room temperature. the measurements showed that keeping the dies at 160°C consumes around 1.9 kW. Instead, keeping the dies at 300°C requires on average 3.7 kW.

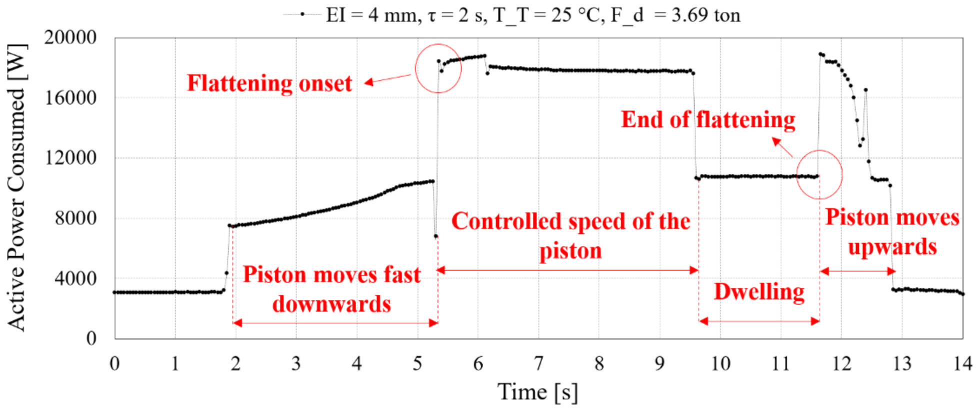


Fig. 4. Press power consumption during the flattening of a DC 04 specimen (0.8 mm) characterized by EI = 4 mm, τ = 2 s, T_T = 25 °C, F_d = 3.69 ton.

Table 1. Power consumption for different conditions tested.

Condition	Power consumption [W]	Duration
Idle phase, T_T = 25 °C	~ 3200	-
During dwelling, EI = 4 mm, T_T = 25 °C, $F_d = 3.69$ ton	~ 11000	Variable: 2 s or 60 s.
During dwelling, EI = 4 mm, T_T = 25 °C, $F_d = 92.15$ ton	~ 13000	Variable: 2 s or 60 s.
Heating dies, from 25 °C to 160 °C	~ 11000	≈ 25 min.
Dwelling, EI = 4 mm, T_T = 160 °C, $F_d = 3.69$ ton	~ 11500	60 s
Keep the dies at 160 °C (steady state)	~ 1900	-
Heating dies, from 160 °C to 300 °	~ 11000	≈ 30 min
Keep the dies at 300 °C (steady state)	~ 3700	-

Life-Cycle Assessment (LCA) of Remanufacturing a Car Roof

The experimental procedure presented in the previous Section is referred to a hydraulic press suited for flattening only parts inscribable in a circle with 6 mm diameter. Nevertheless, the measurements with LEM sensors were helpful to model the profile of power consumption of a press designed for flattening large panels (see Table 2), and to make reasonable hypotheses for setting up the LCA presented in the next Section.

In the framework of sustainable reuse of resources and materials, a LCA of the remanufacturing process was set up, focusing on the remanufacturing by flattening of two EoL panels, cut out of a car roof. In order to define the energetic inputs of flattening large and thin steel panels, the data reported in Table 2 have been used. These data refer to the technical performances of a hydraulic press designed and used exactly for the purpose of flattening sheet metals. The LCA is set-up with the aim of evaluating the embedded energy and the equivalent kgCO$_2$ emissions of the remanufacturing process chain and compare these values with the same indicators of:

- Sheets produced starting from virgin ore. According to a study performed by WorldSteel Association [29], the energy requirement for producing 1 kg or rolled steel (using a "cradle-to-gate" approach) is equivalent to 25.4 MJ, emitting approximately 2.35 kgCO$_2^{Eq}$. These values are close to others published by SSAB [30] and Arcelor Mittal [2].
- Sheets produced from EAF-based recycling plants, without the addition of DRI (Direct Reduced Iron) [31]. According to the work of Suer et al. the production of one kg of rolled steel is associated with a GWP = 0.74 kgCO$_2^{Eq}$ and a CED = 11 MJ.

Assumptions for Setting Up the LCA

- The two panels are extracted by means of an electric cutter from a car roof, which in turn is extracted from the chassis of the EoL car itself in 100 s. The power of the electric cutter is 1400 W. The cutting time of the panels from the roof is 360 s. The same cutter is used for both operations. These disassembly operations at the actual state are not employed by car recyclers, therefore they represent a crucial stage for the reshaping purposes presented. Furthermore, it is fundamental that the EoL panels are not damaged, thus becoming unrecoverable with this routine.
- The two flattened panels have a nominal area of 800x400 mm and 800x700 mm, a nominal thickness of 1 mm and total approximate weight of 6.9 kg. The entire car roof cut from the chassis of the car has a weight of 21 kg. The data presented were directly measured and are referred to a roof extracted from EoL FIAT Punto.
- The portion of the roof not used during flattening is assumed to follow the same recycling path that would have and EoL car, i.e. shredding, magnetic separation, melting in EAF, casting and

rolling. The LCA includes the stage of painting removal as well: for the mechanical de-coating phase, technical data of a commercial sheet metal brusher have been used, whose average power consumption is 4000 W and the operative time for brushing two panels is approximately 280 s. Considering a thickness of paint of 100 µm and the nominal area of the 2 panels (both sides) and considering the average automotive paint density (850 kg/m^3), the amount of paint removed by the brusher is around 150 g. This mass is assumed to be treated in an incineration plant.

- In the analysis, the impacts associated to metal scraps in the second station (namely the roof scrap, see Fig. 5) are not take into account because the study wants to assess the environmental benefits of recycling by reshaping a portion of the roof instead of smelting the same mass (i.e. 6.9 kg). What is not “re-shapable” for a second life by flattening is, in any case, assumed to follow the conventional recycling framework.
- For the calculation of the energy for flattening, Fig. 6 with the relative information reported were used. The analysis is not considering the wear of the various components such as press dies.

Table 2. Technical information of the hydraulic press used for flattening thin sheet metal panels.

Parameter	Value
Max tonnage	420 ton
Max tool temperature	300 °C
Maximum oil pressure	210 bar
Max pump throughput	70 L/min
Oil reservoir volume	500 L
Diameter pressing piston	505 mm
Max power principal electric motor (pump)	15 kW (30 A)
Max power heating system upper die	9.6 kW (14 A)
Max power heating system lower die	9.6 kW (14 A)

Hydraulic press designed for flattening sheet metal panels. Courtesy of Pezzato s.r.l.

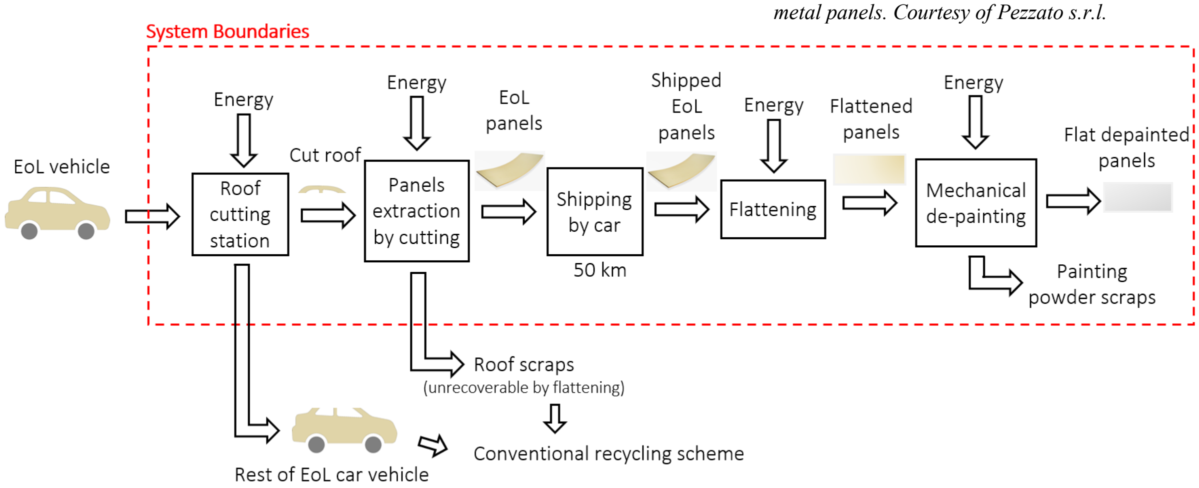


Fig. 5. Definition of the system boundary and flattening process chain with all inputs and outputs.

For determining the energetic input of the press for one flattening cycle, the following assumptions have been used: the press works for 8 hours/day; during the first hour, the press is consuming energy only for heating the dies (for 60 minutes at a power of 20 kW). The other 7 hours the press is performing flattening cycles. During this period, an average power consumption of 10 kW is assumed considering the contribution of idle stage (set-up), flattening and keeping the dies in temperature. Consequently, the total energy consumed is 90 kWh/day. Assuming the duration of one flattening cycle equal to 50s and the available working time, 504 parts per day can be flattened. Each cycle is consuming ≈ 0.18 kWh. For processing two panels, as in this case, a total energy of 0.36 kWh is absorbed by the hydraulic press. The software used for performing the LCA is SimaPro, with Ecoinvent 3 database.

Table 3. Data used for the LCA.

Stage	Input energy [kWh]	Input material	Output material
Roof cutting station	0.038	Dismantled EoL car	Cut roof (21 kg) + Rest of EoL car vehicle*
Extraction of two EoL panels by cutting the roof	0.14	Cut roof (21 kg)	2 bent EoL panels (6.9 kg) + Roof scraps* (14.1 kg)
Shipping by road vehicle of the 2 panels – 50 km by lorry (> 32 ton – EUR 4)	-	2 bent EoL panels (6.9 kg)	2 transported bent EoL panels (6.9 kg)
Flattening 2 panels (2 production cycles)	0.36	2 transported bent EoL panels (6.9 kg)	2 flattened panels (6.9 kg)
Mechanical de-painting of 2 panels (both sides)	0.31	2 flattened panels (6.9 kg)	2 depainted panels (6.9 kg) + paint scrap powder**

* Subjected to conventional recycling by melting, impacts not included in the LCA.
** EoL modelled through landfill incineration.

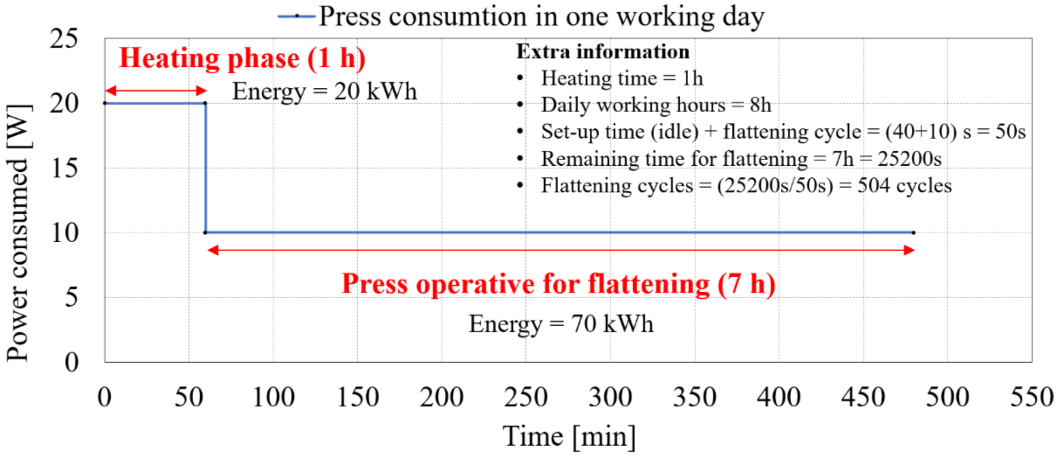


Fig. 6. Press consumption with additional information.

Results of the LCA and Discussion

The main results of the LCA analysis are summarized in Fig. 8, Fig. 7 and Table 4. Data in Table 4 are normalized with respect to 1 kg of flattened automotive steel panel (1 mm thick) or rolled virgin steel. The table highlights the benefits in terms of CO_2 emissions and energy potentially achievable if the proposed reshaping strategy is adopted. The values of Δ_{GWP100} and Δ_{CED} are computed with respect to the case of remanufactured panels.

The left-hand side of Fig. 7 shows clearly that the biggest impacts in terms of CO_2 emissions are related to the painting scrap incineration and electric consumption of flattening (the emissions are computed according to the Italian national energetic mix). The right-hand side of Fig. 7 shows that flattening and de-coating stage have the biggest contributions in energy consumption. Roof cutting station and transportation have negligible impacts, as visible in Fig. 8.

Table 4. Environmental benefits obtained by reshaping EoL panels through flattening.

	GWP100 kg CO_2^{Eq}/kg_{steel}	**CED**[*] MJ/ kg_{steel}	Δ_{GWP100} kg CO_2^{Eq}/kg_{steel}	Δ_{CED} MJ/ kg_{steel}
Conventional process[**]	2.35	25.4	≈ **2.2**	≈ **24**
EAF routine + coil production[***]	0.74	11	≈ **0.6**	≈ **9.6**
Reshaping by flattening[***]	0.144	1.42	-	-

[*] CED = Cumulative energy demand.
[**] Data from literature – Production of steel coils with "cradle-to-gate" approach. [29]
[***] Data from literature – Production of steel coils from EAF-based recycling steel production. [31]
[****] Modelled in SimaPro, including landfill incineration of the paint.

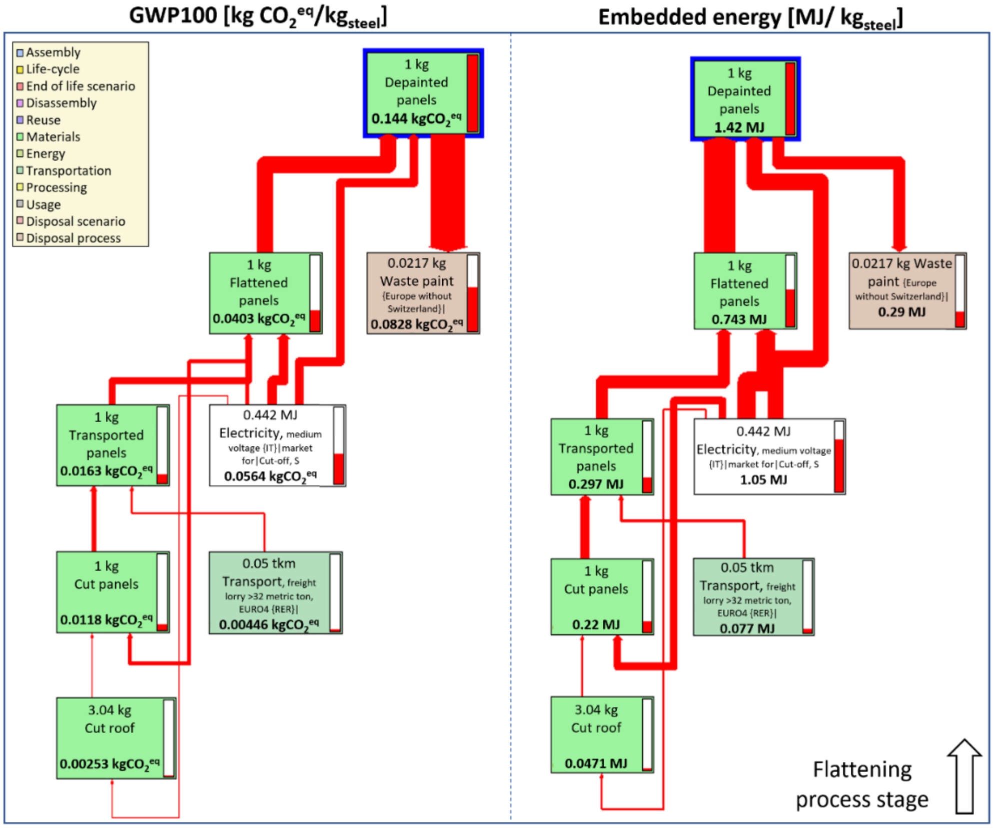


Fig. 7. Results of the LCA analysis with SimaPro.

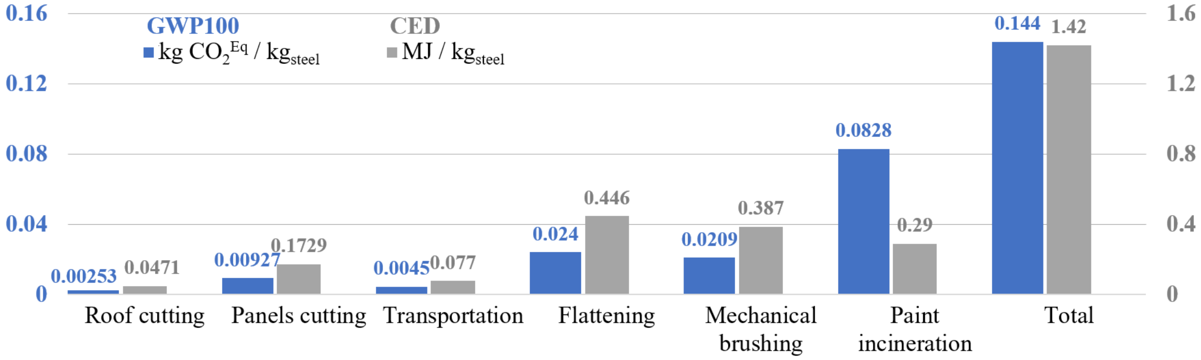


Fig. 8. Different contributions of the different stations in the flattening process chain proposed.

Summary

The work demonstrated different important conclusions, listed below:

- From a technical perspective, flattening is a viable solution for giving a second life to panels deriving from a previous usage (for instance automotive car bodies). The larger the area of the panels to be flattened, the higher the tonnage required by the press, but the higher the "material efficiency" recovered.
- The LEM sensors used for measuring the press power absorption allowed to quantify easily different contributions of energy consumption, such as: moving the piston, idle phases, heating up the dies, keeping the dies in temperature and performing flattening.
- The LCA analysis demonstrates to be a helpful tool to quantify the environmental impacts of all the stages of the flattening process chain. The study showed the tremendous benefits in terms of CO_2^{Eq} emissions and energy that could be potentially achieved by implementing reshaping and remanufacturing strategy of sheet metals.

The implementation of such process chain, considering the huge volumes of EoL cars, could be a potential strategy for reusing efficiently sheet metals in a circular economy business model for automotive car makers or car dismantlers. Enhancing material efficiency through remanufacturing and reshaping is therefore a solution for boosting the ecological transition and meeting the future targets of net zero CO_2 emissions. Lastly, it is important to mention that flattening shaped and formed sheet metals is not always feasible, especially for EoL components with high strains and thinning levels.

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