White paper

The “Circular Economy Formula” CEF

March 2022

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1 Summary / recommendation

Summary

A new way of modelling of secondary products (materials, energy, parts, …) as input to and output from product systems has been developed: the Circular Economy Formula (CEF)[1], has been developed.

The basic idea of this approach is that everything that is kept in the loop, i.e. handed back to the economy during End of Life or waste treatment is credited to the analysed product system, everything that is lost (e.g. to landfill or via downcycling) is the remaining burden/impact of the analysed product system, jointly with the burden/impact from the End of Life and waste treatment processes[2]. This also motivates the name: "Circular Economy Formula", as it incidentally drives product systems towards a perfect Circular Economy, i.e. with minimised material and energy losses and as little as possible burdens from operating EoL and waste treatment processes.

In addition to implementing this in a formula for use in LCA, a second key element is introduced for all cases where downcycling occurs: that of an additional point of reference (to complement the point of substitution), to ensure that downcycling factor is acting exclusively on the relevant parts of the life cycle.

Benefit of the CEF

The new Circular Economy Formula CEF provides a conceptually sound approach and formula, purely attributional and without making assumptions of future uses of recycled materials and other secondary products. It importantly avoids unintended greenwashing and intentional results engineering, what includes that there cannot be anymore artefacts of net negative impacts: such cases occurs wherever an open-loop logic is followed in crediting at end of life. Finally, importantly, the data input to implement the CEF is comparable to similar approaches, often less information and easier to obtain information is required.

Recommendation

We recommend using the CEF in attributional LCA.

Way forward

We recommend that cases and scenarios should be calculated to obtain quantified results. Those examples can draw on real, new cases or remodel existing studies. Also, it is recommended to explore extremes cases that can be encountered in reality but that may not have occurred in the selected studies.

The analysis – best in comparison to other methods – would need to test data availability, clarity/unambiguity of the application, the resulting reproducibility and robustness, and plausibility of decision support, including its directional plausibility when varying input data/parameters. Finally, some other method provisions (e.g. how to model biogenic carbon with a "0" or "-1/+1" approach) need to be considered, as they interact, hence cannot be freely combined in some important cases.

[1] Not to be confused with the Circular Footprint Formula (CFF) of the European Commission.

[2] This basic idea is originating from the reasoning and descriptions in [Koffler & Finkbeiner; 2017]. This present report uses it as input to further develop our previous work on end of life modelling in form of the Integrated formula and the Umbrella formula 2013 to 2026, plus solving further hitherto open aspects.

2 Towards a suitable formula

2.1 The closed-loop circularity logic of the CEF

Conventional credit/debit approaches (also called recyclability substitution, 0/100 and net avoided burden), including the European Commission's Circular Footprint Formula (CFF) have in common that they model the specific (or average) future uses of any recycled material or recovered energy when assigning credits. These credits are hence e.g. the cradle-to-gate Life Cycle Inventory of primary electricity grid mix or the specially superseded (avoided) materials (e.g. the cradle-to-gate Life Cycle Inventory of primary produced concrete and wood as credit low quality mixed plastic regranulate, that would be assumed to be used for park benches and fence posts).

The Circular Economy Formula (CEF) in difference applies an attributional logic of modelling the end-of-life treatment of products and of production waste considering exclusively crediting impacts that are associated and attributable to the analysed system itself, without making assumptions about hitherto unknown future uses of the to-be-recycled material or recovered energy: The system expansion works with the originally attributed burdens (i.e. from the products' cradle-to-gate production chain) that are fully or partly preserved and handed on to the market of secondary products in form of recycled materials, refurbished parts, recovered energy etc. to subsequent uses. Partly the materials, contained energy and other product qualities are also lost to emissions, to landfills etc. as well as via a qualitative loss (i.e. downcycling). This loss is what is the remaining impact assigned to the analysed product system.

This logic can be well imagined and explained to both experts and non-expert stakeholders with two images:

First, from **the image of the perfect circular economy, where there are no losses (recycling rate = 1), what means that only the recycling efforts "to keep the material in the (circular) economy" matter. And when and where losses from the economy occur, those losses are accounted for**. Hence also the name of the new formula that is proposed more below: Circular Economy Formula (CEF).

Secondly, the analogy to Resource dissipation: resources are lost at the moment they are dissipated (to emissions, landfills etc.) and the impact of this loss of access to the resources is modelled at this point of loss, i.e. the point of dissipation, and not anymore when the resources are extracted from the earth, as in $ADP_{elements}$. Identically, also the attributed/embodied impacts from producing a material are lost only when it is lost from the technosphere as e.g. emission, going to landfill, etc. This means that the new idea presented here is analogous to that of Resource dissipation, what will ease external communication/explanation. Hence, formally, there is not anymore a credit/debit thinking and logic, but a loss logic**: what is not lost is kept as "backpack" burden attributed to the secondary material, energy etc.** and handed over to the next products that use the recycled material as recycled content, the recovered energy as secondary energy input, etc. and from there on to the second next uses and along the subsequent uses until all of the contained "value" is lost, as all products system will one after

the other lose a part of the value due to incomplete recycling. However, for the reasons explained in the footnote, the credit/debit "narrative" and modelling logic should be kept[3].

The good thing is that this change can be done even without fundamental changes to how recycled content and recycling are modelled currently in approaches that use the crediting at EoL or production waste treatment and the corresponding debit for recycled content and other secondary goods.

The above changes necessitate, as first new element of the CEF, that the term for crediting at end of life is not simply the market mix or specific superseded primary product, as usually done, but the specific mix of the originally used primary input (e.g. primary material content) and the attributed primary burden for the secondary input (e.g. recycled content); more about this more below.

The following figures illustrate the concept of the attributional crediting/debiting behind the CEF, for the example of the steel belt in tires: the material flow is shown in Figure 1, then the credit debit logic for the contained primary steel in Figure 2, and finally the contained recycled secondary steel content in Figure 3 (all numbers are illustrative only, no real data):

[3] This would call for assigning the loss of attributed/embodied environmental impacts due to imperfect end-of-life treatment to the losses. This leads however to substantial practical and stakeholder acceptance problems: one would need to assign specific impact profiles (i.e. the cradle-to-gate profile (mixes) of producing the specific material that is lost from the technosphere from a specific product or production waste) to all emission flows, tailing flows, waste flows, etc. that contain this material. All these loss flows would have even to be doubled up many times, for all specific products with different material sourcing mixes and their specific cradle-to-gate impact profiles. This is very impractical to implement in LCA software and databases. Practically, that would also mean to substantially correct the model and model structure of all LCI models in secondary databases and in databases at users, from the current credit/debit logic to a loss-based logic. Finally, this would make cradle-to-gate data sets have often substantial negative impacts, what will look odd to non-experts, face greenwashing accusations, and will arguably not be appreciated by many stakeholders. As to decision support, while this approach makes clear where losses actually occur, the use for product design decision choices (i.e. which material to use) would be very indirect, as the impacts would be assigned, as said, to the loss flows, not the production flows.

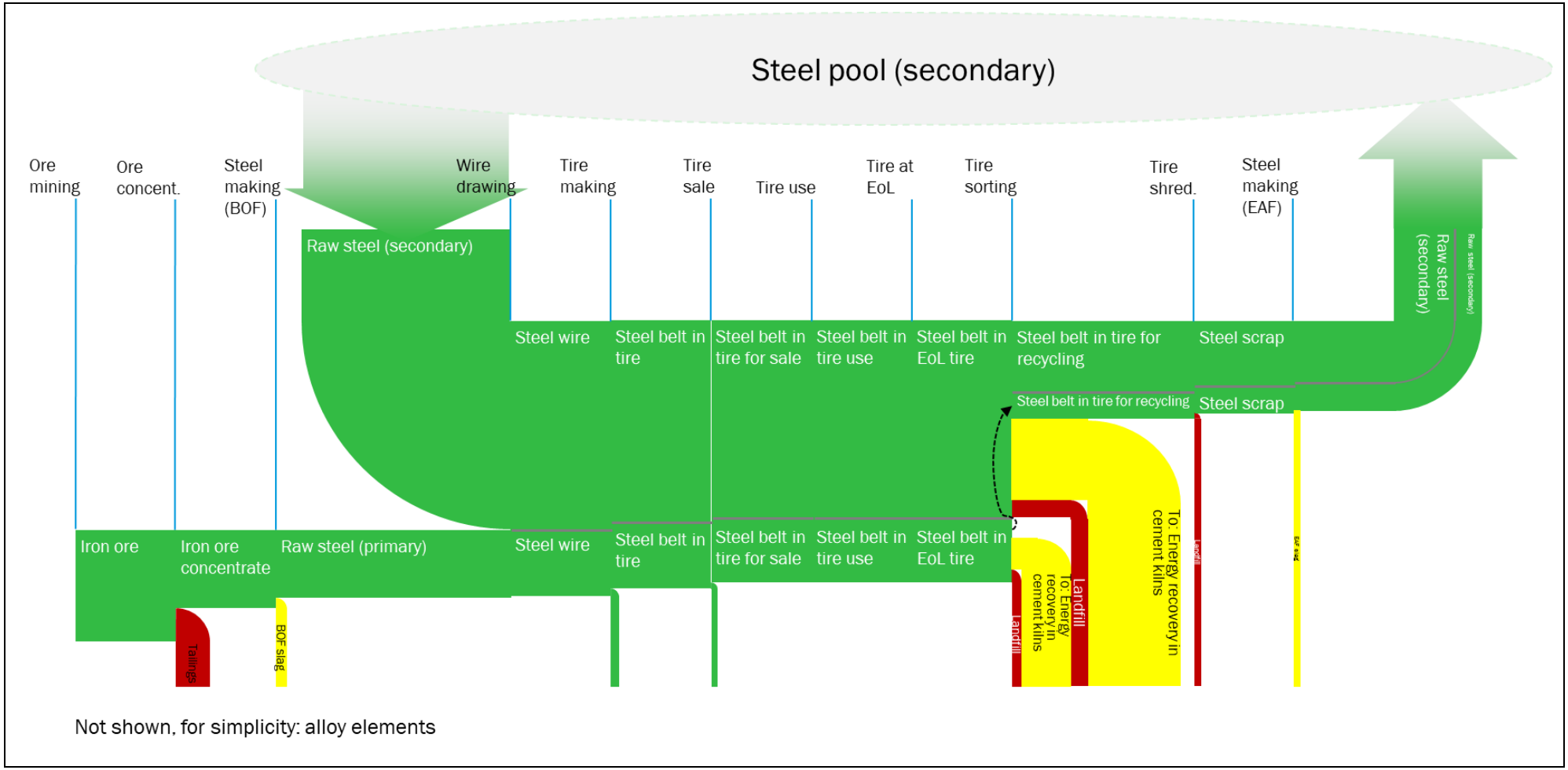

Figure 1 **Material flows – tire steel belt of primary and secondary steel mix, with EoL routes. Thickness of arrows = mass steel (iron) per steel belt. Illustrative only, not actual data.**

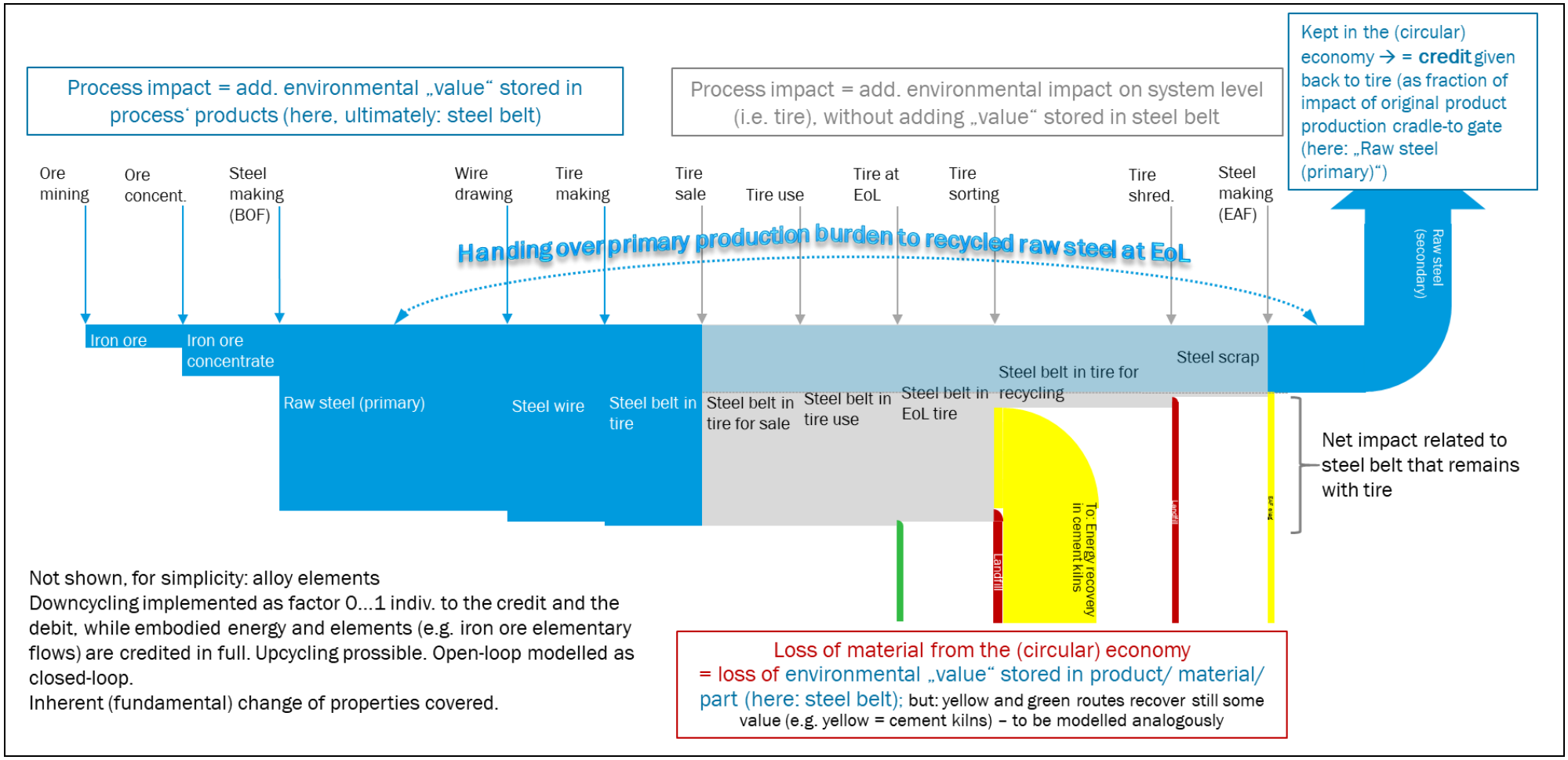

Figure 2 Impact flow of share of primary steel belt, incl. credit at EoL. Thickness of arrows = impact (e.g. climate change) per kg steel belt. Illustrative only, not actual data. Note that the credit at EoL depends on how the contained primary steel has been produced: if this would be some kind of green primary steel (e.g. geothermal or PV-based hydrogen-reduced steel), the credit would be for this specific green steel production.

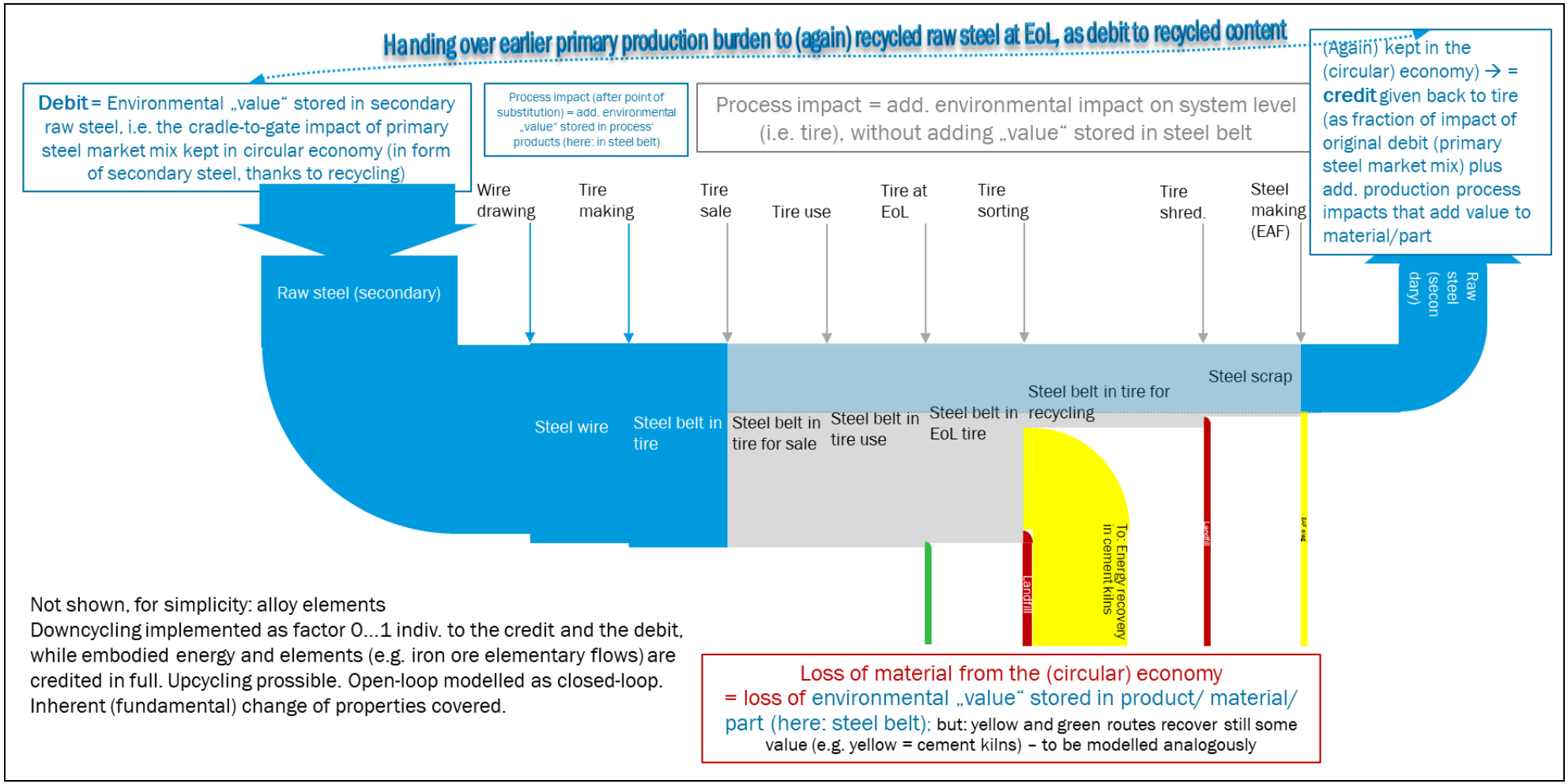

Figure 3 Impact flow of share of secondary steel belt, incl. debit of recycled content and credit at EoL. Thickness of arrows = impact (e.g. climate change) per kg steel belt. Illustrative only, not actual data. Note that the credit and debit for recycled steel is always the market mix, to ensure the credit/debit balance and considering that the recycled content stems from a common pool of recycled steel.

The CEF formula that represents the above[4] reads as follows:

$$E = \sum_{i,j}\left[\left(1 - Rin_{i,j}\right) \times Ev_{i,j} + Rin_{i,j} \times \left(Ev_{i,j}^{m-} + Epos_{i,j}^{m-} \times \frac{Qsin_{i,j}}{Qp_{i,j}}\right)\right]$$

$$+ \sum_{i,j,\,k}\left[Reol_{i,j,\,k} \times Eeol_{i,j,k}\right.$$

$$\left. - Reol_{i,j,\,k} \times \eta_{i,j,k} \times \left(\left[1 - Rin_{i,j}\right] \times \left(Ev_{i,j}^{-} + Epos_{i,j}^{-} \times \frac{Qsout_{i,j}}{Qp_{i,j}}\right) + Rin_{i,j} \times \left(Ev_{i,j}^{m-} + Epos_{i,j}^{m-} \times \frac{Qsout_{i,j}}{Qp_{i,j}}\right)\right)\right]$$

Where:

E: specific emissions and resources consumed (per functional unit) of the material and energy input and output part of the analysed product system, i.e. without manufacturing (beyond the point where primary and secondary material, part, energy etc. enter the production), distribution and use stage.

i is the index of the individual material, part, energy form etc.

j is the index of the component, assembly or other part or fraction of a product or a waste fraction, if modelled, treated and/or assessed separately

k is the index of the end-of-life treatment path, including material recycling, monomer/chemical recycling, raw material recycling, repair, refurbishing, waste incineration (with or without energy recovery), landfilling (with or without landfill gas use), …

Rin: proportion of material, part(s), energy, … in the input to the production that has been recycled/refurbished/recovered… from a previous system (for materials also known as "recycled content").

Ev: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of primary material, part, energy, … used as input in the production of the product.

Evm: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of the market mix of the primary material that corresponds to the secondary material that is used as recycled content in the production of the product. (Note that the same formula component is used for part refurbishing and using them, and for energy recovery and use of secondary energy, etc.; in the full formula an index is used to distinguish all the forms of end of life treatment and secondary materials etc. that are used as input.)

Qsin: quality of the ingoing secondary material (recycled content), part, energy…., at the point of substitution (i.e. the same point of substitution as used in current substitution approaches, not the point of reference as used in addition in the CEF). The default meaning of "*Q*" is the market price; other meanings can be prescribed.

Qsout: quality of the obtained secondary material, part, energy…., at the point of substitution. The default meaning of "*Q*" is the market price; other meanings can be prescribed.

Qp: quality of the primary material, part, energy,.... The default meaning of "*Q*" is the market price; other meanings can be prescribed.

[4] Note: The reasoning behind other elements of the formula is found in the following chapters.

Reol: proportion of the material, part(s), energy, … in the product that will undergo the respective end-of-life treatment path *k*, e.g. material recycling, monomer/chemical recycling, raw material recycling, repair, refurbishing, waste incineration (with or without energy recovery), landfilling (with or without landfill gas use), … . Note that *Reol* is input-based, i.e. the amount/share that goes into the treatment, not the share/amount that comes out of it, which is obtained by multiplying the input amount with the efficiency (yield) factor.

η: Efficiency of the end-of-life treatment path *k*, as quantitative yield of the obtained material, part, energy, … per amount of input of material, part, …. *i*. Note that where the type of output fundamentally/inherently differs from the input (e.g. parts are recycled to materials, a material or whole product is incinerated to recover electricity and heat), the η refers to the ratio of energy yield (e.g. electricity from waste incineration in MJ) divided by energy amount physically stored in the incinerated product/part/material (e.g. MJ HCV per amount of *Reol*). The overall achieved recycling rate can be obtained for information/reporting purposes as *Reol * η* (also e.g. per material, per part, or overall, as wished).

Eeol: specific emissions and resources consumed (per unit of analysis) arising from the end-of-life treatment process (chain), including collection, sorting and transportation process, as applicable. (Note that other than in some approaches, the ErecContent or similar is not required under CEF.)

Evm^{-}: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of market mix primary material, part, energy, … at the last point in the production chain ("point of reference"), where the secondary material, part, energy, … is still fully equivalent to its primary counterpart, i.e. where *Qsin = Qp*.

$Eposm^{-}$: specific emissions and resources consumed (per unit of analysis) arising from those processing steps of the market mix of processes between the point of reference of the Ev^{-} and the physical point of substitution.

Ev^{-}: specific emissions and resources consumed (per unit of analysis) arising from the acquisition and pre-processing of actually used primary material, part, energy, … input at the last point in the production chain ("point of reference"), where the secondary material, part, energy, … is still fully equivalent to its primary counterpart, i.e. where *Qsin = Qp*.

$Epos^{-}$: specific emissions and resources consumed (per unit of analysis) arising from those processing steps of the actually used processes between the point of reference of the Ev^{-} and the physical point of substitution.

Importantly, the very same data source and LCI modelling is to be used for Evm^{-}, $Eposm^{-}$, Ev^{-}, and $Epos^{-}$ to ensure exactly what is lost from the cycle is the remaining impact attributed to the analysed product system.

Note that it can happen in rare cases with a very low *Qsin/Qp* and a high *Qsout/Qp* and high recycling rate $Reol_{i,j,k}$, that the overall results and impacts can be negative. However, that is not greenwashing but actually plausible, as this is representing a strong, innovative upcycling, i.e. where quality of the material is substantially increased in a loop at a lower environmental impact from this upcycling process than the gained quality of the secondary material or product that is obtained from that process. I.e. if in such cases the effort of recycling (*Eeol*) is low, a correct, net negative result can occur in such cases.

Then, in all cases without downcycling lowering the quality of both the ingoing secondary product (e.g. recycled content) and the outgoing secondary product from waste and EoL

product treatment (e.g. recycled materials or refurbished parts obtained), i.e. where *QSin/QP* = *Qsout/QP* = 1, such as for many products made from metals or glass, next to these two downcycling terms also the terms that refer to the point of reference can go, as the point of substitution and the point of reference are identical. The formula hence simplifies in those cases to:

$$E = \sum_{i,j}\left(1 - Rin_{i,j}\right) \times Ev_{i,j} + Rin_{i,j} \times Evm_{i,j} + \sum_{i,j,k}\left[Reol_{i,j,k} \times Eeol_{i,j,k} - Reol_{i,j,k} \times \eta_{i,j,k} \times \left(\left[1 - Rin_{i,j}\right] \times Ev_{i,j} + Rin_{i,j} \times Evm_{i,j}\right)\right]$$

This is also the formula variant that captures what the above graphics depict, while the full CEF captures two additional aspects that we explain the following chapters.

Complexity of the CEF, required input data

We note that we introduce the two indices *i* and *j* that are needed, wherever a product consists of more than one component/assembly, and more than one material. Then, the index *k* allows combining material recycling, energy recovery and landfilling into a common term, while also covering automatically all other forms of EoL treatment, such as digestion or co-digestion to biogas, chemical recycling (to monomers, to syngas, to …), generic parts refurbishment, etc.

Considering this completeness of coverage of all kinds of secondary products, all routes, and for all distinctly handed parts of complex products, the CEF is simpler and less input data demanding particularly for open loop recycling, than conventional substitution/crediting approaches, as particularly three more demanding parameters are not required anymore: The LCI data of the assumed future superseded processes/product and the relative quality (*Qsout, Qp)*.

3 Explaining further specifics of the Circular Economy Formula

3.1 Challenges

3.1.1 Applying the downcycling factor at the point of substitution

3.1.1.1 What is the issue?

This chapter explains the distortion that comes in current substitution approaches due to the quality correction factor *Qs/Qp* being applied to the entire inventory of the credit (and the same for the debit) at the point of substitution, and how the CEF corrects this:

The problem is that *Qs/Qp* acts on the complete inventory of the credited product, while the downcycled aspect is arguably only in the last process step(s) towards e.g. a purified material, or a part or component. An example: if a generic plastic part is being refurbished, due to aging and as the part is possibly being scratched during its use and overall having a shorter life time than a primary part, it is likely to be considered somewhat downcycled after refurbishing. This is captured by default by *Qs/Qp,* expressed per default as market price ratios. However, the plastic part's energy content is still 100% the same as that of the new part, also the plastic content and hence the initial effort to produce the plastic granulate is still the preserved in the refurbished part. What is lost, are exclusively parts of the "value" of producing the part itself from the granulate, i.e. a share of the last production step. The idea to take this insight quantitatively into account is to complement the currently used point of substitution by a "point of reference" where the recycled part (or material, energy carrier, …) is fully equivalent (here, probably: the plastic granulate) and to give 100% credit for that LCI at that point (i.e. *Ev* of plastic granulate). Plus give a partial credit (downscaled by *Qs/Qp*) of the next process step(s) towards the actual/physical point of substitution (here: the part), i.e. a partial credit of the part production process LCI[5].

The key is to recognise that applying a quality downcycling factors *Qs/Qp* at input or output on the entire inventory of the primary material, part, energy, … inevitably leads to a distortion where embodied energy and elements (including carbon) are scaled down, while they are physically still contained in the obtained recyclate or used secondary material or part. This can be (and sometimes is) corrected by so-called carbon-correction, particularly for contained carbon (and including differentiating biogenic and fossil carbon), to avoid implausible overall CO_2 emissions and climate change impacts. However, this is costly/resource demanding and needs to be done for each and any contained element and energy. As we have argued, the downcycling moreover does not act on the whole upstream chain but typically on the last processing step(s) only; the carbon correction cannot capture this distortion. This is the – case-wise quantitatively highly relevant – additional correction that the CEF achieves, as follows:

[5] If – as to be expected, in rare cases - during this last process step(s) between the old and new point of substitution additional elemental resources/energy are physically embodied into the material or part, these additionally embodied resource flows would need to be 100% assigned to the recycled material, refurbished part etc. and not be subject to the downcycling factor *Qs/Qp*.

3.1.1.2 How the CEF addresses this issue

Figure 1 illustrates the concept, with the example of a polypropylene part that undergoes various end-of-life treatments, some with some quality loss, i.e. downcycling. In conventional quality-correction, the downcycling factor is applied on the cradle-to-gate inventory at the physical point of substitution (top graphic). In the CEF, for all cases of downcycling, the credited/debited cradle-to-gate chain is shorter and the downcycling factor applied to the processing step(s) to the processing steps between the point of reference and the physical point-of-substitution (bottom graphic). In Figure 1 this is the case for the recycled PP granulate and the refurbished PP part. The following graphics show this and the adjusted credit:

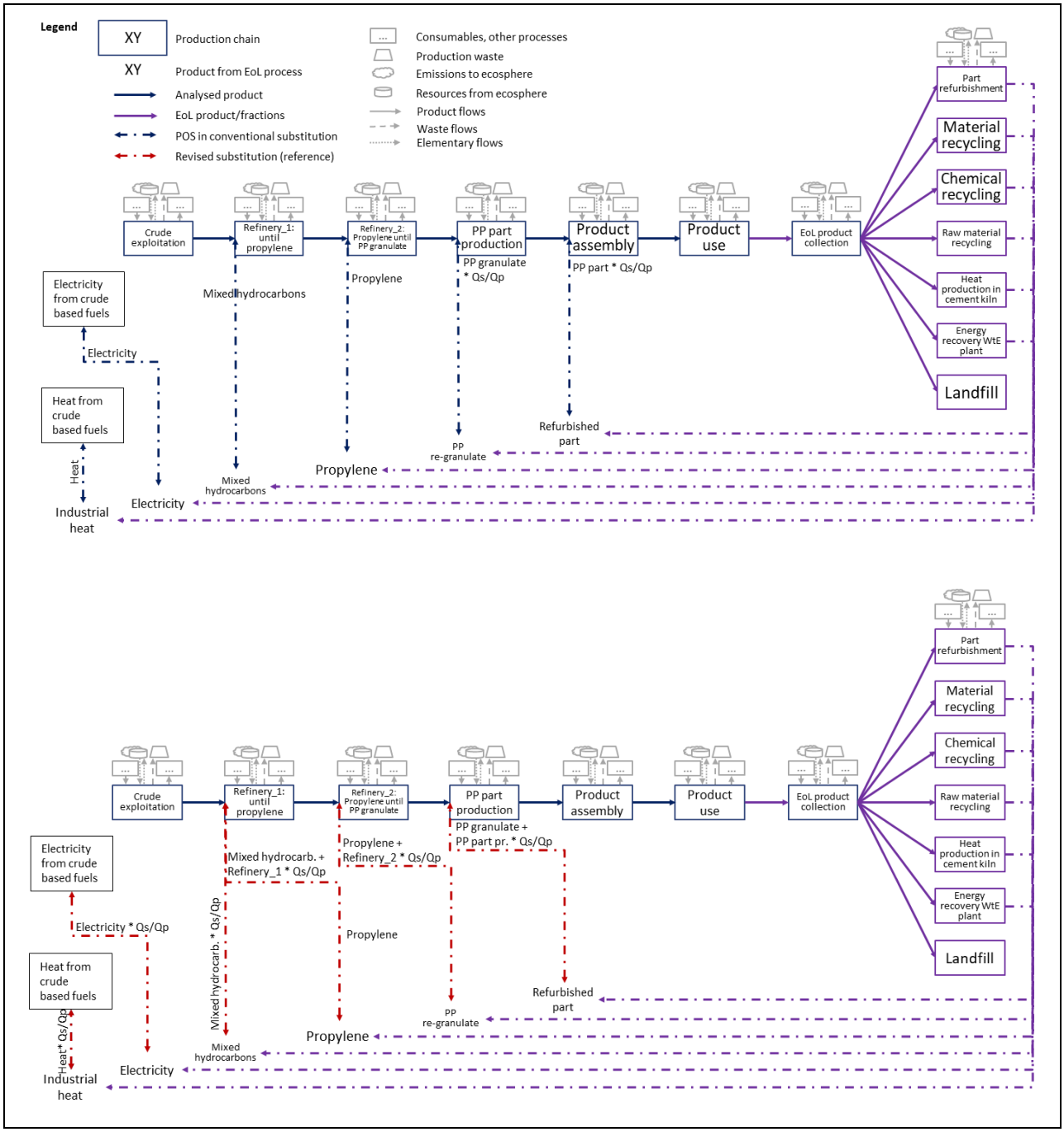

Figure 4 Conventional crediting and debiting (top graphic) and newly proposed crediting and debiting with downcycling factor exclusively applied to the last, relevant processing step(s) between the point of substitution and the point of reference (bottom graphic, in the CEF).

This change is improving the accuracy of the crediting and debiting, even substantially, wherever *Qs/Qp* are increasingly smaller than 1. The effort to model this is somewhat higher, as two credits are to be given: the full one at the point of reference and the partial (downcycled) one for the process step(s) towards the recycled part/product. Also the LCI data of those process step(s) is needed in addition (while the needed LCI data will typically be available already, as different recycling levels already occur now and hence those inventories are anyway needed and/or available at the producer).

Note that there are specific cases where *Qs/Qp* is smaller than 1 but where the point of reference is not existing. An example is recycling of products made from natural fibres: if the recovered fibres are shortened or of mixed colours, they would arguably yield a market price that is lower than that of the equivalent primary fibres they are made of. As the fibre cropping (e.g. cotton) is the first production step, there is no point of reference along the life cycle process chain where fibres or another product status exist of 100% equivalent quality (unless the unprocessed cotton crop in the field, while that is of another kind of quality). In that case, the downcycling factor is logically to be applied to the whole cradle-to-gate chain of the cotton cropping, harvesting and fibre separation.

3.1.2 Open loop with fundamental change of inherent properties

3.1.2.1 What is the challenge?

A practical challenge is when a more fundamental change to the inherent properties occurs, i.e. not just a downcycling of primary plastics in e.g. bio-based packaging material to a mixed plastics secondary granulate that can only be used for simpler applications such as fence posts or park benches, while still being plastics. A more fundamental change and hence a true open loop case occurs when e.g. the same bio-based packaging plastic material is incinerated with energy recovery in form of electricity or heat that was not part of the biomass growth or plastics synthesis to this extent and is hence not physically embodied in the bioplastic. Or when the bio-plastic may be transformed via chemical recycling to a substance or mix of substances (e.g. pyrolysis oil, syngas) that did not occur upstream in the bioplastics production chain. In this case, the EoL treatment is not merely extracting the material or part as it was all the time present in the product, but is fundamentally transforming it, fundamentally changing its inherent properties.

This situation is further complicated by the fact that often the amount of energy recovered e.g. in form of electricity from waste-to-energy may be higher than the energy that has been employed along the life cycle and that is now physically stored in the material. Such increase of energy content from electricity (and hence NOT forming the aforementioned problem) may indeed be found e.g. for thin aluminium foil, where electricity and other energy carriers were used to mine, enrich, and reduce the ore to the metallic aluminium, roll the thin aluminium foil (i.e. the aluminium part that is lost during waste incineration), which now at least releases its energy, generating a single specific secondary product: electricity (or possibly with heat as co-product). For other products, e.g. wood products, this will not be the case, as the energy stems from solar energy embodied during tree growth plus efforts for cutting an sawing etc. to obtain the piece of wood, which from waste-to-energy treatment at its end of life again delivers electricity (or possibly with heat as co-product), or – in a landfill – some landfill gas. None of these energy carriers in these amounts were part of the wood product cradle-to-gate inventory that were recovered: the embodied energy is mostly that of the sun. For yet other cases, the embodied energy stems mostly from fossil sources, but did not enter much in form of

electricity, but mostly as natural gas or crude oil as raw material source and for process heat (e.g. in plastics). These different situations hence need to have specific guidance how to identify which credits are to be given and how to scale the different nature and quality of e.g. ingoing crude as energy carrier against the secondary electricity output, were a simple *Qs/Qp* correction does not work well.

In any case and for most cases, as to what was present in the product, typically most if this will be destroyed/lost, typically all structure (e.g. fibre, sheet) or part forming. Often also the material itself may be lost, leaving the secondary products either with exclusively the primary energy content (such as in the examples of electricity and steam from waste incineration) or in addition the contained elements (mostly carbon or simpler CxHy compounds, such as in the case of pyrolysis oil or syngas), rarely adding new elements for obtaining high value materials (as in the example of chlorinating some organic waste to obtain specific chlorinated chemicals as secondary products). However, this EoL treatment step also adds value to the resulting product beyond the mere contained energy and chemical elements. In some cases the transformation may even add elements as exemplified above. The challenge is then to carve out which part of the EoL treatment and its inventory is to be assigned to the source (i.e. the EoL product) and which to the downstream secondary product.

3.1.2.2 Point of substitution/ Point of reference[6] in such cases

Closely intertwined with the above is the question of the actual point of substitution i.e. where is the boundary between the two product systems: taking the example of waste tires used as fuel (and also as iron source, but we keep it simple and do not look at this aspect) in cement rotary kilns, two very different perspectives are found:

- The tire industry would usually assume that the tire is replacing other (primary) energy sources at the kilns (e.g. natural gas or fuel oil). The tire system would hence get as credit the equivalent amount of primary fuel according to the physical energy content of the waste tires.
- The cement industry would usually take the perspective to consider the tire incineration as a waste treatment service that they perform, hence would assign the emissions of the incineration to the tires[7] and credit exclusively the avoided fuels (e.g. natural gas) as credit.

The implications of the point of substitution for decision support are important. For the tire example: if the specific emissions of tire incineration would be carried by the downstream user, there would be no incentive to take cleaner incineration behaviour into account in tire development. If in turn the emissions would be fully assigned to the tires, there would be no incentives to reduce emissions in the cement kiln (aside legal obligations, of course). The price/fee of the tires, delivered to the kiln, is an indicator if this is rather a waste treatment process, or rather available secondary fuel sold to the kiln. In the 1990s as example fees for waste tires were in the range 0.25 up to 1 US$. At a typical value of 7 kg/tire, this is 45 up to 180 EUR/t (early 1990s). More recent fees in the US and in the EU in the period 2010 to 2020 were roughly in the range of 10 to 50 EUR/t waste tires, in Australia up to 120 EUR/t. Hence, the use in cement kilns (with the fee covering the extra needed handling equipment) can be

[6] See also on the general case, as applicable to closed loop in chapter 3.1.1

[7] Interestingly, a study by Nakomcic-Smaragdakis et al. in 2016 showed that – compared to coal and petroleum coke - using waste tires as a relevant share in the fuel of a Serbian cement kiln did not change the SO2 and NOx emissions significantly. For liquid and gaseous fuels and solid fuels with lower sulphur content, the results may be different, though.

argued to be a waste treatment process, analogous to waste-to-energy plants or landfills with landfill gas recovery are. The point of substitution would hence be not the tire as a solid fuel, but the usable energy generated in that process as well as the steel's material contribution to the Portland cement, after its oxidation.

3.1.2.3 What to credit in such cases under the CEF?

The credit (i.e. for what has been recovered from the original production system of the tire) is very early in the production chain. This is argued to be at least:

- the embodied fossil and renewable primary energy (for the rubber part), plus arguably the effort to get it out of the ground/the plantation (please see more below what that entails), and
- the contained iron resource flow and arguably the iron ore production itself (as it is a physically contained part of the Portland cement from the kiln).

However, the specific quality of the electricity is higher than the contained fossil or renewable energy, same as e.g. recycled metallic copper has a higher quality and hence receives a higher credit than merely the contained copper resource elementary flow. The specific quality depends on the specific recycling/recovery process that allows to not only recover a contained resource elementary flow but something more than that, a product, i.e. it adds a new value that has not been there before, here: electricity. As we do not see at the moment any exact concept and a better reproducible set of rules how to take this aspect into account, we propose to put as credit the minimum needed cradle-to-gate inventory to generate electricity (or heat) (with the same energy yield and from an equivalent production route). I.e. for fossil rubber this would be an as simple and as clean as available light fuel oil electricity (or heat) production process, for natural rubber a wood based electricity or heat, both modelled as operated in the country or region where the material stems from, i.e. not where it is EoL treated(!).

Does that make sense: This approach has the plausible effect that even in an extreme case (say: a simple wood block used as chair for ten years, then incinerated in a highly efficient wood mono-incineration CHP) would first get the EoL treatment inventory assigned (i.e. with the emission profile and consumables of the highly efficient and clean mono incineration CHP) and then get deducted the credit for the very same "electricity & heat from wood in a highly efficient and clean mono-incineration CHP". In sum, the wood chair would retain only its specific processes needed to carve out the wood chair block from the wood, i.e. a small but not negative impact, reflecting that there was in fact little extra impact caused by using the wood block as a chair for ten years. Would the wood have been directly incinerated instead of first using it as a chair for ten years, the electricity and heat would be the same inventory as the credit. Hence from both product system and downstream and alternative use perspectives, even in this extreme scenario, this approach seems to make sense. Under the conventional market mix or specific crediting approaches, the electricity and heat from the wood chair EoL – in contrast - would be equal to the grid mix and the wood chair inventory would be possibly net negative for many impact categories, given that this grid mix would be the credit, assigned to a product whose production impact is barely more impacting than that of a piece of raw wood.

3.2 Situations encountered and how they are to be represented in the CEF

Four different situations are encountered for EoL treatment or waste treatment, as to the kind of secondary products obtained and their quality (i.e. downcycling):

A) **"Closed loop without downcycling":** The secondary product is of the same type as it has been present in the product or production waste (i.e. no fundamental change to inherent properties: e.g. secondary aluminium is still aluminium[8], i.e. not converted to recovered energy during waste incineration) and has no significant downcycling at the physical point of substitution (i.e. is of the same quality and market price as primary aluminium).

B) **"Closed loop with downcycling":** The secondary product is of the same type as it has been present in the product or production waste (i.e. no fundamental change to inherent properties: e.g. refurbished polypropylene part or assembly (e.g. a printer cartridge) is still a polypropylene part or assembly, i.e. not converted to recovered energy during waste incineration), but has relevant downcycling at the physical point of substitution (i.e. is of lower quality (here: lower technical life time) and hence a lower market price than the primary part/assembly). Still, it is used in the same application type (i.e. "bottle to bottle" situation).

C) **"Open loop with downcycling but no fundamental change of inherent properties":** As B), but the secondary material/part etc. is used in other types of applications ("bottle to textile" situation). This case is not differentiated from the above case "Closed loop with downcycling" by us[8,9], i.e. modelled as closed loop This is in line with what ISO 14044 calls "open loop modelled as closed loop".

D) **"Open loop with fundamental change of inherent properties":** The secondary product is of a different type than it has been present in the EoL product or production waste (i.e. there is a fundamental change to inherent properties: e.g. syngas or electricity from plastic waste chemical recycling or from waste incineration, respectively). Downcycling means in this case that the obtained secondary material or energy has a lower quality compared to the primary material or energy that it is replacing at the physical point of substitution; it hence has a lower market price than the primary part/assembly and *Qs/Qp* is lower than 1. As discussed in the preceding chapter, for cases where the EoL-treated product undergoes fundamental inherent changes, e.g. to electricity and/or

[8] The term closed loop is used in slightly different ways by different practitioners: the „closed" can refer to the kind of product an e.g. material is used in (e.g. an aluminium can is recycled and that secondary material is used to again to produce an aluminium can and not e.g. an aluminium profile). Another usage refers to the question if the material sees some downcycling during recycling, i.e. "closed" means that it returns in the same quality as it went into the analysed product. We use the second definition, already as it is not known and except for rare exceptions also not knowable in which other products the recycled material will be used (such an exception would be a take back scheme with own operation of the eol treatment, plus selling the secondary material to specific uses/users or use it in own production): the recycling happens somewhen in the future by typically unknown recyclers that sell the secondary aluminium on the market, where it enters a range of future uses, depending exclusively on the quality and availability. See also the next footnote.

[9] The term „closed loop", used to represent cases where a recycled material is entering the „same" production process, is in fact conceptually undistinguishable from the "open loop" situation: e.g. a recycled plastic from EoL PET bottles is always used in a new product (e.g. a new bottle), even if the very same machine, as the bottle is not the same bottle and moreover usually already used to fill different drinks by different producers. In other words: there is no true closed loop anyway. What matters is exclusively a) if there is downcycling and b) if there is a fundamental change of inherent properties.

heat or to landfill gas, the question arises, what is the point of substitution and point of reference, and the appropriate *Ev* and *Evm* and the value for *Rin*. We have already described in chapter 3.1.2 the recommended approach to solve this situation including what to credit.

4 References

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