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LC-NMBP-29-2019
Materials for non-battery based energy storage (RIA)

RECYCALYSE: New sustainable and recyclable catalytic materials for proton exchange membrane electrolysers

D8.3: Preliminary analysis and first recommendations on circularity

Date: 29-07-2022

This document is part of the RECYCALYSE project 861960 corresponding to D8.3 lead by DTI.

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+ RECYCALYSE -

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Contents

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1. Executive summary

Part of the focus of the RECYCALYSE project is to increase the circularity of the proposed PEMEC solution. The Material Circularity Indicator, MCI, and the included Linear Flow Index, LFI, are used to indicate the circularity of the pilot scale PEMEC solution developed through the various WPs of the RECYCALYSE project.

The MCI calculation focus only on the mass of materials without consideration of resource scarcity (e.g. identical focus on iron and platinum). The calculations in RECYCALYSE are performed only with the metals within the membrane electrode assembly (MEA), mainly consisting of critical raw materials (CRMs), e.g. iridium, ruthenium etc., to avoid being dominated completely by the use of steel and stainless steel.

Information is collected from the other WPs and a calculation is performed on the material consumption, and materials being lost out of a circular system, due to not being collected or due to being lost in the recycling process.

Three calculations are performed

- Default scenario with virgin materials as input, production waste is not collected, and final product is collected for recycling after use.
- Alternative 1 where the collected material after use is recycled and used to provide recycled content in the input material
- Alternative 2 where all production waste is collected, recycled, and used to provide recycled content of the input material.

The MCI value in general varies between 0,1 and 1. The default PEMEC solution ends up with a calculated value of an MCI of 0,41. The MCI goes up to 0,72 in alternative 1 when using the collected materials instead of virgin input material. The MCI values reaches a maximum of 0,94 in alternative 2 when recycling and using all production waste to provide recycled content of input material.

2. Goal and scope

The goal of the circularity screening assessment is to give a first indication of the circularity of the assessed PEMEC system.

The calculation is performed on the metals within the MEA, mainly consisting of Critical Raw Materials (CRMs) characterized by being scarce and having a high impact on production. For the initial circularity calculations this is covering the materials in Table 4.1.

The entire calculation could be done on the complete system including all operation and control equipment (manometers, pumps, valves etc). The masses of this equipment would operate in the order of magnitude of 10-100kg. The material consumption in Table 4.1 and recovery as calculated in WP7 (Table 4.3), operates at the scale of single digit grams or lower, and any effects of material consumption and recovery of CRMs would be negligible. The circularity

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would be calculated only on the control and system equipment and neglect the circularity of the CRMs; hence the entire purpose of the RECYCALYSE project would be ignored.

3. Calculation methodology

There is a broad political consensus that circular economy is beneficial. However, there is currently no scientific consensus on how this is assessed. This consensus is currently being sought for in technical working groups such as ISO/TC 323 on Circular economy (www.iso.org).

Various comparisons for possible indicators are carried out, see for example:

- https://circulareconomy.europa.eu/platform/sites/default/files/summa_-_indicators_for_a_circular_economy.pdf

One of the currently most completed approaches is the MCI set of calculation routines, that seeks to indicate:

- Recycled input is beneficial over virgin material input
- Capture of unrecoverable losses; material lost directly due to washout on non-collection or through losses in recycling processes are selected against.
- An increase in utility is calculated as increased efficiency or increased lifetime compared to the average industrial product on the market.

A description of the methodology is carried out in parallel to the calculations

3.1 Calculation routine

The screening calculations are based on the Material Circularity Index[1] (MCI) from the Ellen MacArthur Foundation.

The methodology was expanded in 2019 to include material of sustainable biogenic origin that can be composted or incinerated for energy recovery. These topics are irrelevant for the RECYCALYSE project and are not handled.

The explanation below is a very brief outline; for a complete description see the complete methodology description through the footnote link.

3.1.1 Mass of virgin feedstock

Each mass of material, M, has an input of virgin material, V, which does not come from recycled, F_R, or reused sources, F_U.

$$V = M(1 - F_R - F_U)$$

[1] https://ellenmacarthurfoundation.org/material-circularity-indicator

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3.1.2 Mass of unrecoverable waste

There is an initial waste loss W_0. Essentially, it is the mass of material, M, deducting what is lost due to not being collected for recycling, "- C_R", or to reuse, "- C_U", see the formula below.

$$W_0 = M(1 - C_R - C_U)$$

There are losses in the recycling processes happening at the end of life after use, W_C, and to supply recycled feedstock as input material, W_F.

The recycling material loss due to loss in recycling efficiency, E_C, is accounted for as W_C. It is only applied to the fraction actually collected for recycling C_R:

$$W_C = M(1 - E_C)C_R.$$

The loss in the recycling process to produce recycled feedstock material as recycled content input is accounted for as W_F. The efficiency of the recycling process is E_F, and fraction F_R:

$$W_F = M\frac{(1 - E_F)F_R}{E_F},$$

The formula is slightly different as it needs to increase the input material needed to supply an output of recycled material included waste loss; hence the E_F factor in the denominator.

An overall amount of unrecoverable waste, W, is calculated as:

$$W = W_0 + \frac{W_F + W_C}{2}$$

There is a 50/50 calculation done including waste during recycling for feedstock material W_F and for recycling after use W_C. This is done since recycled material does not undergo a recycling twice; one at collection and one before reuse. This would lead to a double counting of recycling loss.

3.1.3 Linear Flow and Material Circularity Index

The Linear Flow Index (LFI) measures the proportion of material flowing in a linear fashion, that is, sourced from virgin materials and ending up as unrecoverable waste:

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$$

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The index takes a value between 1 and 0, where 1 is a completely linear flow and 0 a completely restorative flow. There are two correction factors "$+W_F/2$" and "$-W_C/2$" that are explained in the background methodology[2].

The calculation of the utility of the system can give a bonus X to an increase in lifetime compared to an average industrial product (L/L_{av}) and to an increase in output production or utility compared to an average industrial product (U/U_{av})

$$X = \left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right)$$

This consideration is not taken into account in this screening calculation. Part of the purpose of the RECYCALYSE project is to increase the production per active catalytic unit; hence the utility will be handled further in deliverable 8.4.

The Material Circularity Index (MCI) is constructed to preferably create a value from a minimum of 0,1 to a maximum of 1 when not taking into account the X utility factor above:

$$MCI^*_P = 1 - LFI \cdot F(X). \qquad F(X) = \frac{0.9}{X}$$

4. Default system calculation

4.1 Material and loss per production step

The calculation routing can be expanded to cover the individual components and sub-assemblies, as produced by the different WPs in RECYCALYSE.

This leads to the creation of a calculation routine including the catalyst material efficiency of the different WPs and the need for additional material to account for this loss.

The calculation starts at the catalyst material content of the final stack and works backward through the production processes in each WP. There is a calculation of material losses and subsequently higher input material, as well as material loss not being collected or being lost in inefficient recycling. This is indicated in Figure 1 below with the example of Sn. This calculation example is covered through the outline of the processes.

[2] https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o

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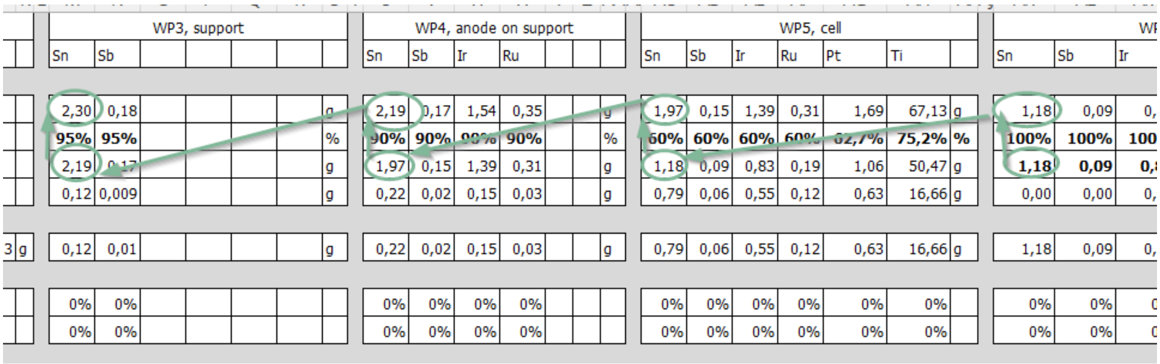

Figure 1. Structure of mass flows in MCI, and LFI calculation, representing the flow quantities in grams of each metal from support, to anode, to cell and stack production. Units in % represents the output yield based on input.

WP5 Final product (and WP6 use)

The MEA metal content of the final stack is outlined in Table 4.1 below. The mass is calculated from a total of 14 cells at 7,07g/piece = 98,9g of cells. This is split into cathode catalyst, anode catalyst on support, titanium, cathode gas diffusion layer (GDL) and membrane. Furthermore, these are split onto sub-components and down to single metals. The green bold numbers are hence the metals included in the circularity calculations as the starting point of calculation.

Table 4.1: MEA metal content of final stack

Component	**Overall level**		**Sub-components**		**Sub-level**	**Single component**
Cathode catalyst	2%	2,3 g				
			Platinum		46%	**1,06 g**
Anode catalyst on support	4%	3,5 g				
			ATO(*)		43%	1,53 g
				SnCl4	170%	2,60 g
				Sn	45%	**1,18 g**
				SbCl3	11%	0,17 g
				Sb	53%	**0,09 g**
			IrCl3		43%	1,50 g
				Ir	55%	**0,83 g**
			RuCl3		13%	0,44 g
				Ru	42%	**0,19 g**
Titanium felt						
	51%	50,5 g	Titanium			**50,5 g**
Cathode GDL	15%	14,7 g				
Membrane	28%	27,9 g				
Cell total	100%	98,9 g				

(*) Antimony doped tin oxide

The calculations are performed with 100% collection with some underlying assumptions:

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- All the material is collected without loss during collection
- The material is not washed out during use
- If material is washed out from the cell/stack it is collected in water filters

WP5 cell production

The MEA materials form the content of the final product and WP5, final stack (in bold in Table 4.1).

The input material from "WP5, final stack" serves as the output material from "WP5, cell". A yield between 60%-75,2% results in a higher input material, as calculated in Table 4.2 below. The yield is applied to the appropriate metal.

Table 4.2: Yield of WP5 cell production

Parameter	**Input, g/cell**	**Output, g/cell**	**Yield**	**CRMs concerned**
Cathode Catalyst	0,26	0,16	62,7%	Pt
Cathode GDL	1,40	1,05	75,0%	
Membrane	2,66	2,00	75,0%	
Titanium Felt	4,80	3,61	75,2%	Ti
Supported catalyst from WP4	0,42	0,25	60,0%	Sb, Ir, Ru

A calculation example is performed for Sn

- Output material = 1,18g; yield = 60%
- Input material = 1,18g/60% = 1,97 g
- Material loss = 1,97g – 1,18g = 0,79g

These values can be found under "WP5, cell" in the outline in Figure 1.

WP4 anode on support

The anode catalyst on support production has achieved a yield of approx. 90% during pilot production. Calculations parallel to Table 4.2 are not performed.

An example calculation is performed on Sn, outlining the material loss and need for material input..

- Output material = 1,97g; yield = 90%
- Input material = 1,97g/90% = 2,19 g
- Material loss = 2,19g – 1,97g = 0,22g

These values can be found under "WP4, anode on support" in the outline in Figure 1.

WP3 support

The support production has achieved a yield of approx. 95% during pilot production. Calculations parallel to Table 4.2 are not performed.

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An example calculation is performed on Sn, outlining the material loss and need for material input.

- Output material = 2,19g; yield = 95%
- Input material = 2,19g/95% = 2,30 g
- Material loss = 2,30g – 2,19g = 0,12g (rounded)

These values can be found under “WP3, support” in the outline in Figure 1.

4.2 Material aggregation

The material generation is calculated per production step per material as calculated in the example for tin, Sn. This is transferred to the row “-delta mass”, including also the mass of the final product.

The individual losses of material are summarized to give a final material consumption of the PEMEC stack. In the calculation in Figure 4, this sums up to 73,2g to the left in the table under the “Total calculations” columns and the row “-delta mass”.

4.3 Calculated losses

For each “Delta material” is indicated how much of the material is collected for recycling (C_R) or reuse (C_U). This is used to calculate the direct material loss as not collected (W_0). For the example of Sn, see Figure 2, there is a Delta mass in “WP5 cell” of 0,79g which is not collected for recycling or reuse. It is transferred to a material loss of:

W_0 = 0,79g.

This corresponds to 1,18g of Sn from the final stack that it is collected for recycling. The recycling efficiencies from WP7 that are used in the LCA calculations, see Table 4.3, are used to calculate losses from the recycling process.

Table 4.3: Metal content and recovery in recycling

Metal content	Content, g	Recovery %	Output from recycling, g
Pt	1,06	96%	1,02
Ir	0,83	90%	0,75
Ru	0,19	93%	0,17
Sn	1,18	94%	1,11
Sb	0,09	92%	0,08
Ti	50,47	93%	46,99

There is hence no direct material loss but instead a material loss of 0,07g in the recycling process, W_C:

W_C = 1,18g x 100%collected x (1-94%) = 0,07g.

This loss is seen in Figure 2.

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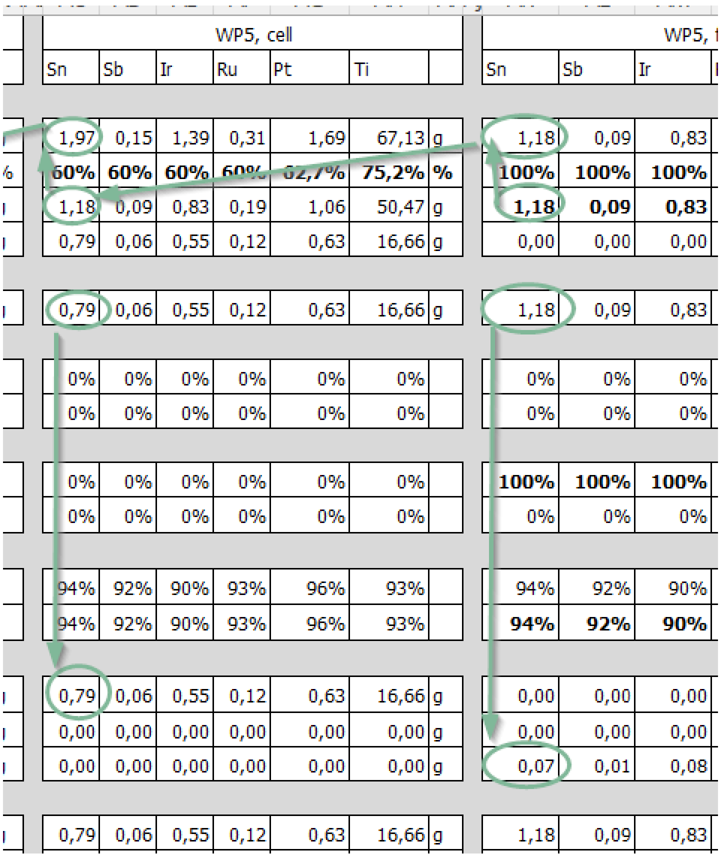

WP5, cell							WP5,		
Sn	Sb	Ir	Ru	Pt	Ti		Sn	Sb	Ir
1,97	0,15	1,39	0,31	1,69	67,13	g	1,18	0,09	0,83
60%	**60%**	**60%**	**60%**	**62,7%**	**75,2%**	**%**	**100%**	**100%**	**100%**
1,18	0,09	0,83	0,19	1,06	50,47	g	**1,18**	**0,09**	**0,83**
0,79	0,06	0,55	0,12	0,63	16,66	g	0,00	0,00	0,00
0,79	0,06	0,55	0,12	0,63	16,66	g	1,18	0,09	0,83
0%	0%	0%	0%	0%	0%		0%	0%	0%
0%	0%	0%	0%	0%	0%		0%	0%	0%
0%	0%	0%	0%	0%	0%		**100%**	**100%**	**100%**
0%	0%	0%	0%	0%	0%		0%	0%	0%
94%	92%	90%	93%	96%	93%		94%	92%	90%
94%	92%	90%	93%	96%	93%		**94%**	**92%**	**90%**
0,79	0,06	0,55	0,12	0,63	16,66	g	0,00	0,00	0,00
0,00	0,00	0,00	0,00	0,00	0,00	g	0,00	0,00	0,00
0,00	0,00	0,00	0,00	0,00	0,00	g	0,07	0,01	0,08
0,79	0,06	0,55	0,12	0,63	16,66	g	1,18	0,09	0,83

Figure 2. Calculation of waste in MCI calculation

For each delta material there is also the indication of how much of the material has an origin as recycled (F_R) or reused (F_U). In the reference scenario all material has a virgin origin and these fractions are zero.

A scenario calculation is performed with an assumed loop of the recovered metals serving as recycled content on the input side. For Sn this adds up to 48% recycled content. In this case there is a calculation loss of the metal during the recycling process. Here the calculated loss of material during the feedstock recycling is calculated as W_F:

$$W_F = 1{,}18\text{g} \times 48\% \text{ from recycled} \times (1-94\%) / 94\% = 0{,}04\text{g}.$$

The 94% efficiency is the efficiency reported from WP7 during active recycling.

4.4 Virgin input and unrecoverable waste

The virgin is calculated as the full mass of material subtracted what has an origin as recycled (F_R) or reused (F_U). For the default scenario, all material is of virgin origin.

A scenario calculation is performed with an assumed loop of the recovered metals serving as recycling input. For Sn this adds up to 48% recycling content; still with a reused content of 0. The virgin input of Sn to the material in the final hence becomes:

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V = 1,18g x (1- 48% - 0%) = 0,61g

The unrecoverable waste is calculated as the sum of waste lost due to not being collected, ½ of the waste lost in the recycling process to supply recycled content, and ½ of the waste generated in end-of-life recycling. In the default scenario, for the mass of Sn in the final product, the value unrecoverable waste loss, W, becomes.

W = 0 g (not collected) + ½ x 0,07 g (eol recycling) + ½ x 0 g (feedstock) = 0,035 g

Note that 0 g are lost due to not being collected. All waste after use is assumed collected for recycling and therefore 0g lost due to not being collected.

The two material indicators, virgin input (V) and unrecoverable waste (W) is summarized for all the processing steps and all the included resources, giving the totals for the entire life cycle. In the calculation Excel sheet this is done towards the left of the sheet.

For the default scenario, the values become

V = 73,19g

W = 21,21g

4.5 LFI calculation

The LFI is calculated as the virgin material V plus the unrecoverable waste W, divided with twice the mass 2M, and taking into account the two correction factors "+W_F/2" and "-W_C/2". The sources of the numbers are found in the leftmost data column in Figure 4.

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}}$$

= (73,19g + 21,21g) / (2 * 73,19 + ½*0g - ½*3,69g)

= 0,65

4.6 Lifetime and utility calculation

There are no assumptions done for the default screening scenario on the lifetime and output production of the RECYCALYSE system i.e. the factors (L/L_{av}) and (U/U_{av}). The utility function therefore becomes

X=1

and the function

F(X) = 0,9/X = 0,9

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4.7 MCI calculation of default scenario

The MCI calculation of the default system is now

MCI = 1 – 0,65 * 0,9

= 0,41

5. Alternative scenario calculations

5.1 Alternative 1: Recycled content with default collection

The first additional scenario is calculated assuming that the recovered material in WP6 with the recycling efficiencies reported from WP7 are used as inputs to the system. For Sn the collected material is

Collected = 1,18g * 100% collected * 94% recycling efficiency

= 1,11g

The total mass consumption of Sn including the supply chain losses is 2,30g, see Figure 4

Therefore, the recycled content becomes

Recycled content = 1,11g / 2,30g = 48%

This recycled material from end-of-life would therefore be able to supply the input material with a recycled content of 48%. The other materials are supplying from 47% - 70% recycled content.

The calculation is performed in Figure 5. The result is

- a decrease in the linearity of the materials; LFI 0,65→ 0,32
- an increase in the material circularity; MCI 0,41→ 0,72

5.2 Alternative 2: Recycled content with all collection

The second additional scenario is performed with an assumed collection of the waste happening also in the production of the cells in WP5, anode-on-support material in WP4, and support material in WP3. The materials collected from each WP is found in the green cells in Figure 6. The summarized material collection and the calculation of max recycled content is calculated in the blue section of Figure 6. When collection the waste from all WPs the recycled content per material can now be 90%-96% as indicated in the blue section in Figure 6.

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The calculation is performed in Figure 6. The result is compared to the first additional scenario

- a decrease in the linearity of the materials; LFI 0,65→ 0,07
- an increase in the material circularity; MCI 0,41 → 0,94

5.3 Summing up on scenarios

The circularity calculation is performed on a default scenario and two alternatives;

- Default scenario using data from the relevant WPs of the RECYCALYSE project.
- Alternative 1 with the end product collected and the material used to supply recycled material
- Alternative 2 with all the waste material (from support, anode on support, cell and stack production) collected and used to supply recycled material. The output of the calculation of the Linear Flow Index, LFI, and Material Circularity Index MCI, is given below in Figure 3.

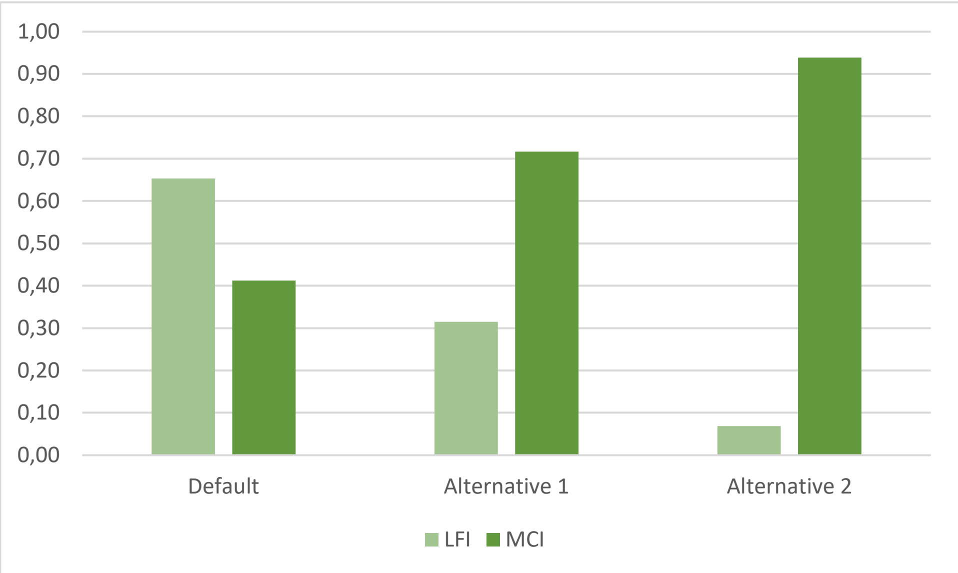

Figure 3: LFI and MCI values of all scenarios

6. Discussion

The result from a default scenario ends up with and linear flow value of LFI=0,65, indicating that 65% of the material acts in a linear fashion. This corresponds to a circularity index value of MCI=0,41. Considering that the index value primarily acts from 0,1-1 with 1 being good, this indicates that the value is quite low.

Furthermore, there are some critical assumptions included.

- All metals from the MEAs of the produced stack are recovered for recycling.

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- Metals are not washed out during operation and is thereby not collected for recycling.
- The utility and lifetime of the stack compared to industry average is not taken into account.

The first values can be improved as indicated by the alternative scenarios:

- Using the collected metals from the stack to provide recycling material on the input side makes the LFI value go down to 0,32 and even lower to 0,07, hereby indicating that only 7% of the material acts in a linear fashion. The remaining acts in a circular fashion.
- The MCI goes up to 0,72 and collecting all production waste maximizes the MCI at 0,94.
- The remaining index up to 1 is not obtained due to losses in the recycling process.

7. Future

The present report is a screening as an initial approach to evaluate the circularity of the RECYCALYSE PEMEC stack. Some future developments will take place towards the final delivery.

7.1 Utility and lifetime

The material circularity indicator contains an inclusion of the expected lifetime and expected functional performance compared to industry average; the L and U values under chapter 3.1.3

As there is an objective of the RECYCALYSE project to prolong lifetime; this would increase the L value.

There is an objective of the RECYCALYSE project to increase the output per g catalytic material. This would increase the U value.

These two factors will be investigated in the final delivery.

7.2 CRM vs non-CRM

There is an objective of replacing CRMs with non-CRMs for catalytic materials. The MCI calculation itself has no inclusion of resource-criticality. It only calculates on the collection and recycling of the material without notion of scarcity. Hence, additional non-CRM materials would undergo the same calculations per g material without any predictable change in MCI value.

7.3 Other scenarios from WPs

There will be a consideration of what development scenarios from other WPs that can be evaluated for their effect on circularity.

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7.4 Total mass of non-CRM materials

In the present screening calculations, there is a focus on MEA and CRM materials, as the calculations would otherwise be completely dominated by the metals in much larger quantities (steel, stainless steel, brass etc.).

There will not be a calculation of MCI on the entire solution. This would be exclusively dominated by the much heavier steel, stainless steel, brass, polymer materials etc. of the full PEMEC system. These types of calculation are of low importance to investigate the efficiency of the PEMEC solution.

7.5 Additional indicators

It will be considered if additional impacts to describe circularity should be included in the final circularity assessment.

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Total calculations

Metal		Sum	Sn	Sb	Ir	Ru	Pt	Ti	
Process calculations									
Input material									
Yield									
Output material									
Material loss									
Weights									
- delta mass	M	73,19	2,30	0,18	1,54	0,35	1,69	67,13	g
Non-virgin input									
- from recycled sources	F_R								
- from reused sources	F_U								
Collection									
- for recycling	C_R								
- for reuse	C_U								
Efficiency in recycling									
- feedstock recycling	E_F								
- recycling after use	E_C								
Calculated losses									
- initial loss, not collected	W_0	19,37	1,12	0,09	0,71	0,16	0,63	16,66	g
- loss in feedstock recyc	W_F	0,00	0,00	0,00	0,00	0,00	0,00	0,00	g
- loss in waste recyc	W_C	3,69	0,07	0,01	0,08	0,01	0,04	3,48	g
LFI (Lineal Flow index) calculations									
- Virgin input	V	73,19	2,30	0,18	1,54	0,35	1,69	67,13	g
- Unrecoverable waste	W	21,21	1,16	0,09	0,75	0,17	0,65	18,40	g
- LFI		0,65							
Utility									
- Lifetime	L	10							
- Lifetime, average	L_{av}	10							
- Use int	U	10							
- Use int, average	U_{av}	10							
- Utility	X	1							
- Function F	F(X)	0,90							
MCI									
- Material Circularity Indicat	MCI	0,41							

WP3, support

Metal		Sn	Sb	
Process calculations				
Input material		2,30	0,18	g
Yield		**95%**	**95%**	%
Output material		2,19	0,17	g
Material loss		0,12	0,009	g
Weights				
- delta mass	M	0,12	0,01	g
Non-virgin input				
- from recycled sources	F_R	0%	0%	
- from reused sources	F_U	0%	0%	
Collection				
- for recycling	C_R	0%	0%	
- for reuse	C_U	0%	0%	
Efficiency in recycling				
- feedstock recycling	E_F	94%	92%	
- recycling after use	E_C	94%	92%	
Calculated losses				
- initial loss, not collected	W_0	0,12	0,01	g
- loss in feedstock recyc	W_F	0,00	0,00	g
- loss in waste recyc	W_C	0,00	0,00	g
LFI (Lineal Flow index) calculations				
- Virgin input	V	0,12	0,01	g
- Unrecoverable waste	W	0,12	0,01	g

WP4, anode on support

Metal		Sn	Sb	Ir	Ru	
Process calculations						
Input material		2,19	0,17	1,54	0,35	g
Yield		**90%**	**90%**	**90%**	**90%**	%
Output material		1,97	0,15	1,39	0,31	g
Material loss		0,22	0,02	0,15	0,03	g
Weights						
- delta mass	M	0,22	0,02	0,15	0,03	g
Non-virgin input						
- from recycled sources	F_R	0%	0%	0%	0%	
- from reused sources	F_U	0%	0%	0%	0%	
Collection						
- for recycling	C_R	0%	0%	0%	0%	
- for reuse	C_U	0%	0%	0%	0%	
Efficiency in recycling						
- feedstock recycling	E_F	94%	92%	90%	93%	
- recycling after use	E_C	94%	92%	90%	93%	
Calculated losses						
- initial loss, not collected	W_0	0,22	0,02	0,15	0,03	g
- loss in feedstock recyc	W_F	0,00	0,00	0,00	0,00	g
- loss in waste recyc	W_C	0,00	0,00	0,00	0,00	g
LFI (Lineal Flow index) calculations						
- Virgin input	V	0,22	0,02	0,15	0,03	g
- Unrecoverable waste	W	0,22	0,02	0,15	0,03	g

WP5, cell

Metal		Sn	Sb	Ir	Ru	Pt	Ti	
Process calculations								
Input material		1,97	0,15	1,39	0,31	1,69	67,13	g
Yield		**60%**	**60%**	**60%**	**60%**	**62,7%**	**75,2%**	**%**
Output material		1,18	0,09	0,83	0,19	1,06	50,47	g
Material loss		0,79	0,06	0,55	0,12	0,63	16,66	g
Weights								
- delta mass	M	0,79	0,06	0,55	0,12	0,63	16,66	g
Non-virgin input								
- from recycled sources	F_R	0%	0%	0%	0%	0%	0%	
- from reused sources	F_U	0%	0%	0%	0%	0%	0%	
Collection								
- for recycling	C_R	0%	0%	0%	0%	0%	0%	
- for reuse	C_U	0%	0%	0%	0%	0%	0%	
Efficiency in recycling								
- feedstock recycling	E_F	94%	92%	90%	93%	96%	93%	
- recycling after use	E_C	94%	92%	90%	93%	96%	93%	
Calculated losses								
- initial loss, not collected	W_0	0,79	0,06	0,55	0,12	0,63	16,66	g
- loss in feedstock recyc	W_F	0,00	0,00	0,00	0,00	0,00	0,00	g
- loss in waste recyc	W_C	0,00	0,00	0,00	0,00	0,00	0,00	g
LFI (Lineal Flow index) calculations								
- Virgin input	V	0,79	0,06	0,55	0,12	0,63	16,66	g
- Unrecoverable waste	W	0,79	0,06	0,55	0,12	0,63	16,66	g

WP5, final stack

Metal		Sn	Sb	Ir	Ru	Pt	Ti	
Process calculations								
Input material		1,18	0,09	0,83	0,19	1,06	50,47	g
Yield		**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**%**
Output material		**1,18**	**0,09**	**0,83**	**0,19**	**1,06**	**50,47**	g
Material loss		0,00	0,00	0,00	0,00	0,00	0,00	g
Weights								
- delta mass	M	1,18	0,09	0,83	0,19	1,06	50,47	g
Non-virgin input								
- from recycled sources	F_R	0%	0%	0%	0%	0%	0%	
- from reused sources	F_U	0%	0%	0%	0%	0%	0%	
Collection								
- for recycling	C_R	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	
- for reuse	C_U	0%	0%	0%	0%	0%	0%	
Efficiency in recycling								
- feedstock recycling	E_F	94%	92%	90%	93%	96%	93%	
- recycling after use	E_C	**94%**	**92%**	**90%**	**93%**	**96%**	**93%**	
Calculated losses								
- initial loss, not collected	W_0	0,00	0,00	0,00	0,00	0,00	0,00	g
- loss in feedstock recyc	W_F	0,00	0,00	0,00	0,00	0,00	0,00	g
- loss in waste recyc	W_C	0,07	0,01	0,08	0,01	0,04	3,48	g
LFI (Lineal Flow index) calculations								
- Virgin input	V	1,18	0,09	0,83	0,19	1,06	50,47	g
- Unrecoverable waste	W	0,035	0,00	0,04	0,01	0,02	1,74	g

Figure 4: Default scenario. Calculation of MCI value.

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Metal		Total calculations: Sum	Sn	Sb	Ir	Ru	Pt	Ti	
Process calculations									
Input material									
Yield									
Output material									
Material loss									
Weights									
- delta mass	M	73,19	2,30	0,18	1,54	0,35	1,69	67,13	g
Non-virgin input									
- from recycled sources	F_R								
- from reused sources	F_U								
Collection									
- for recycling	C_R								
- for reuse	C_U								
Efficiency in recycling									
- feedstock recycling	E_F								
- recycling after use	E_C								
Calculated losses									
- initial loss, not collected	W_0	19,37	1,12	0,09	0,71	0,16	0,63	16,66	g
- loss in feedstock recyc	W_F	3,69	0,07	0,01	0,08	0,01	0,04	3,48	g
- loss in waste recyc	W_C	3,69	0,07	0,01	0,08	0,01	0,04	3,48	g
LFI (Lineal Flow index) calculations									
- Virgin input	V	23,06	1,19	0,09	0,79	0,17	0,67	20,14	g
- Unrecoverable waste	W	23,06	1,19	0,09	0,79	0,17	0,67	20,14	g
- LFI		0,32							
Utility									
- Lifetime	L	10							
- Lifetime, average	L_{av}	10							
- Use int	U	10							
- Use int, average	U_{av}	10							
- Utility	X	1							
- Function F	F(X)	0,90							
MCI									
- Material Circularity Indicato	MCI	0,72							

Metal	WP3, support: Sn	Sb		WP4, anode on support: Sn	Sb	Ir	Ru	
Process calculations								
Input material	2,30	0,18	g	2,19	0,17	1,54	0,35	g
Yield	**95%**	**95%**	%	**90%**	**90%**	**90%**	**90%**	%
Output material	2,19	0,17	g	1,97	0,15	1,39	0,31	g
Material loss	0,12	0,009	g	0,22	0,02	0,15	0,03	g
Weights								
- delta mass	0,12	0,01	g	0,22	0,02	0,15	0,03	g
Non-virgin input								
- from recycled sources	48%	47%		48%	47%	49%	50%	
- from reused sources	0%	0%		0%	0%	0%	0%	
Collection								
- for recycling	0%	0%		0%	0%	0%	0%	
- for reuse	0%	0%		0%	0%	0%	0%	
Efficiency in recycling								
- feedstock recycling	94%	92%		94%	92%	90%	93%	
- recycling after use	94%	92%		94%	92%	90%	93%	
Calculated losses								
- initial loss, not collected	0,12	0,01	g	0,22	0,02	0,15	0,03	g
- loss in feedstock recyc	0,00	0,00	g	0,01	0,00	0,01	0,00	g
- loss in waste recyc	0,00	0,00	g	0,00	0,00	0,00	0,00	g
LFI (Lineal Flow index) calculations								
- Virgin input	0,06	0,00	g	0,11	0,01	0,08	0,02	g
- Unrecoverable waste	0,12	0,01	g	0,22	0,02	0,16	0,04	g
- LFI								
Utility								
- Lifetime	**Material collection per WP**							
- Lifetime, average	0,00	0,00		0,00	0,00	0,00	0,00	
- Use int								
- Use int, average								
- Utility								
- Function F								
MCI								
- Material Circularity Indicato								

Metal	WP5, cell: Sn	Sb	Ir	Ru	Pt	Ti		WP5, final stack: Sn	Sb	Ir	Ru	Pt	Ti	
Process calculations														
Input material	1,97	0,15	1,39	0,31	1,69	67,13	g	1,18	0,09	0,83	0,19	1,06	50,47	g
Yield	**60%**	**60%**	**60%**	**60%**	**62,7%**	**75,2%**	%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	%
Output material	1,18	0,09	0,83	0,19	1,06	50,47	g	**1,18**	**0,09**	**0,83**	**0,19**	**1,06**	**50,47**	g
Material loss	0,79	0,06	0,55	0,12	0,63	16,66	g	0,00	0,00	0,00	0,00	0,00	0,00	g
Weights														
- delta mass	0,79	0,06	0,55	0,12	0,63	16,66	g	1,18	0,09	0,83	0,19	1,06	50,47	g
Non-virgin input														
- from recycled sources	48%	47%	49%	50%	60%	70%		**48%**	**47%**	**49%**	**50%**	**60%**	**70%**	
- from reused sources	0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	
Collection														
- for recycling	0%	0%	0%	0%	0%	0%		**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	
- for reuse	0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	
Efficiency in recycling														
- feedstock recycling	94%	92%	90%	93%	96%	93%		94%	92%	90%	93%	96%	93%	
- recycling after use	94%	92%	90%	93%	96%	93%		**94%**	**92%**	**90%**	**93%**	**96%**	**93%**	
Calculated losses														
- initial loss, not collected	0,79	0,06	0,55	0,12	0,63	16,66	g	0,00	0,00	0,00	0,00	0,00	0,00	g
- loss in feedstock recyc	0,02	0,00	0,03	0,00	0,01	0,86	g	0,04	0,00	0,04	0,01	0,02	2,62	g
- loss in waste recyc	0,00	0,00	0,00	0,00	0,00	0,00	g	0,07	0,01	0,08	0,01	0,04	3,48	g
LFI (Lineal Flow index) calculations														
- Virgin input	0,41	0,03	0,28	0,06	0,25	5,00	g	0,61	0,05	0,43	0,09	0,42	15,14	g
- Unrecoverable waste	0,80	0,06	0,57	0,13	0,64	17,09	g	0,05	0,01	0,06	0,01	0,03	3,05	g
- LFI														
Utility														
- Lifetime														
- Lifetime, average	0,00	0,00	0,00	0,00	0,00	0,00		1,11	0,08	0,75	0,17	1,02	46,99	
- Use int				**Totals collected**				1,11	0,08	0,75	0,17	1,02	46,99	
- Use int, average				**Total mass**				2,30	0,18	1,54	0,35	1,69	67,13	
- Utility				**Recycled content**				48%	47%	49%	50%	60%	70%	
- Function F														
MCI														
- Material Circularity Indicato														

Figure 5: Alternative 1. Calculation of MCI; default collection

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Metal		Total calculations: Sum	Sn	Sb	Ir	Ru	Pt	Ti	
Process calculations									
Input material									
Yield									
Output material									
Material loss									
Weights									
- delta mass	M	73,19	2,30	0,18	1,54	0,35	1,69	67,13	g
Non-virgin input									
- from recycled sources	F_R								
- from reused sources	F_U								
Collection									
- for recycling	C_R								
- for reuse	C_U								
Efficiency in recycling									
- feedstock recycling	E_F								
- recycling after use	E_C								
Calculated losses									
- initial loss, not collected	W_0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	g
- loss in feedstock recyc	W_F	5,02	0,14	0,01	0,15	0,02	0,06	4,63	g
- loss in waste recyc	W_C	5,02	0,14	0,01	0,15	0,02	0,06	4,63	g
LFI (Lineal Flow index) calculations									
- Virgin input	V	5,02	0,14	0,01	0,15	0,02	0,06	4,63	g
- Unrecoverable waste	W	5,02	0,14	0,01	0,15	0,02	0,06	4,63	g
- LFI		0,07							
Utility									
- Lifetime	L	10							
- Lifetime, average	L_{av}	10							
- Use int	U	10							
- Use int, average	U_{av}	10							
- Utility	X	1							
- Function F	F(X)	0,90							
MCI									
- Material Circularity Indicato	MCI	0,94							

Metal	WP3, support: Sn	Sb		WP4, anode on support: Sn	Sb	Ir	Ru	
Process calculations								
Input material	2,30	0,18	g	2,19	0,17	1,54	0,35	g
Yield	**95%**	**95%**	%	**90%**	**90%**	**90%**	**90%**	%
Output material	2,19	0,17	g	1,97	0,15	1,39	0,31	g
Material loss	0,12	0,009	g	0,22	0,02	0,15	0,03	g
Weights								
- delta mass	0,12	0,01	g	0,22	0,02	0,15	0,03	g
Non-virgin input								
- from recycled sources	94%	92%		94%	92%	90%	93%	
- from reused sources	0%	0%		0%	0%	0%	0%	
Collection								
- for recycling	**100%**	**100%**		**100%**	**100%**	**100%**	**100%**	
- for reuse	0%	0%		0%	0%	0%	0%	
Efficiency in recycling								
- feedstock recycling	94%	92%		94%	92%	90%	93%	
- recycling after use	94%	92%		94%	92%	90%	93%	
Calculated losses								
- initial loss, not collected	0,00	0,00	g	0,00	0,00	0,00	0,00	g
- loss in feedstock recyc	0,01	0,00	g	0,01	0,00	0,02	0,00	g
- loss in waste recyc	0,01	0,00	g	0,01	0,00	0,02	0,00	g
LFI (Lineal Flow index) calculations								
- Virgin input	0,01	0,00	g	0,01	0,00	0,02	0,00	g
- Unrecoverable waste	0,01	0,00	g	0,01	0,00	0,02	0,00	g
- LFI								
Utility								
- Lifetime	**Material collection per WP**							
- Lifetime, average	0,11	0,01		0,21	0,02	0,14	0,03	

Metal	WP5, cell: Sn	Sb	Ir	Ru	Pt	Ti		WP5, final stack: Sn	Sb	Ir	Ru	Pt	Ti	
Process calculations														
Input material	1,97	0,15	1,39	0,31	1,69	67,13	g	1,18	0,09	0,83	0,19	1,06	50,47	g
Yield	**60%**	**60%**	**60%**	**60%**	**62,7%**	**75,2%**	%	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	%
Output material	1,18	0,09	0,83	0,19	1,06	50,47	g	**1,18**	**0,09**	**0,83**	**0,19**	**1,06**	**50,47**	g
Material loss	0,79	0,06	0,55	0,12	0,63	16,66	g	0,00	0,00	0,00	0,00	0,00	0,00	g
Weights														
- delta mass	0,79	0,06	0,55	0,12	0,63	16,66	g	1,18	0,09	0,83	0,19	1,06	50,47	g
Non-virgin input														
- from recycled sources	94%	92%	90%	93%	96%	93%		94%	92%	90%	93%	96%	93%	
- from reused sources	0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	
Collection														
- for recycling	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**		**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	
- for reuse	0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	
Efficiency in recycling														
- feedstock recycling	94%	92%	90%	93%	96%	93%		94%	92%	90%	93%	96%	93%	
- recycling after use	94%	92%	90%	93%	96%	93%		**94%**	**92%**	**90%**	**93%**	**96%**	**93%**	
Calculated losses														
- initial loss, not collected	0,00	0,00	0,00	0,00	0,00	0,00	g	0,00	0,00	0,00	0,00	0,00	0,00	g
- loss in feedstock recyc	0,05	0,00	0,05	0,01	0,02	1,15	g	0,07	0,01	0,08	0,01	0,04	3,48	g
- loss in waste recyc	0,05	0,00	0,05	0,01	0,02	1,15	g	0,07	0,01	0,08	0,01	0,04	3,48	g
LFI (Lineal Flow index) calculations														
- Virgin input	0,05	0,00	0,05	0,01	0,02	1,15	g	0,07	0,01	0,08	0,01	0,04	3,48	g
- Unrecoverable waste	0,05	0,00	0,05	0,01	0,02	1,15	g	0,07	0,01	0,08	0,01	0,04	3,48	g
- LFI														
Utility														
- Lifetime														
- Lifetime, average	0,74	0,06	0,50	0,12	0,61	15,51		1,11	0,08	0,75	0,17	1,02	46,99	
- Use int				**Totals collected**				2,17	0,16	1,39	0,32	1,63	62,50	
- Use int, average				**Total mass**				2,30	0,18	1,54	0,35	1,69	67,13	
- Utility				**Recycled content**				94%	92%	90%	93%	96%	93%	

Figure 6: Alternative 2. Calculation of MCI; max recycled content

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8. References

Ellen MacArthur Foundation, 2019, “Circularity Indicators, An Approach to Measuring Circularity: Methodology”

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