Renewable Energy 175 (2021) 686–701

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A framework for sustainable evaluation of thermal energy storage in circular economy

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ARTICLE INFO

Article history:
Received 15 March 2021
Received in revised form
20 April 2021
Accepted 24 April 2021
Available online 8 May 2021

Keywords:
Life cycle assessment (LCA)
Circular economy
Material circularity index
Thermal energy storage (TES)
Concentrated solar power
Sustainability

ABSTRACT

The circular economy can be promoted as a solution to support the sustainability market position of renewable energy systems. To design a circular and sustainable system, a structured approach is needed. The present study develops a methodology framework for sustainable circular system design (SCSD), aiming to assess thermal energy storage (TES) technologies from a sustainable perspective. To this end, a composite indicator, namely, environmental sustainability and circularity indicator (*ESC*) is provided. This indicator combines the environmental impacts of the TES system via the conduction of a life cycle assessment and its circulatory performance using the product-level material circularity indicator (*MCI*). The developed methodology is applied to a case study of high-temperature TES using molten salts as a part of a concentrated solar power plant. The SCSD embraces the analysis for the most relevant processes through proposing different ecological scenarios including, increasing the recycling rates (Modest Scenario), increasing the reuse rates (Medium Scenario), and a combination of both (Optimistic scenario). The circularity analysis showed that for the Modest, Medium and optimistic scenarios, the *MCI* moves from 20.6% for the current situation to 30.3%, 38.6%, and 46.4%, respectively. Accordingly, the optimistic scenario showed the most environmentally sustainable and circular scenario with *ESC* of 7.89%, whereas the Modest and Medium scenarios exhibited *ESCs* of 1.20% and 2.16%, respectively. A major obstacle for substantial improvement of the circulatory and *ESC* is the high share of unrecyclable molten salts in the system and therefore, any effort to improve the circulatory and the environmental benefits of this system can be reached by using more environmentally friendly alternative materials. The study concludes that the integration of reusing and recycling at the initial design should be sought in order to achieve a more environmentally sustainable and circular outcome.

1. Introduction

A new series of social hurdles, owing to the massive stress on organizational resources and the massive expansion of the worldwide population. The consumption of oil, food, water, components and other resources has risen, and suppliers are coping with this development [1]. The exponential progress of the world and the rapid growth of developing markets indicate that energy demand is growing, and costs have typically risen after the new century [2]. The European Union approved a new clean energy framework for a sustainable transition from fossil fuel usage to renewable energy following up the EU 2030 greenhouse gases reduction targets [3]. An important step to spread on the clean energy transition in the European Union and its Member States is renewable energy usage. Out of all renewable energy-based systems, solar thermal is the technology that can be expanded from residential applications to urban applications [4].

Concentrating solar power (CSP) plants are becoming the best

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https://doi.org/10.1016/j.renene.2021.04.136

Nomenclature

C_R	Fraction of mass of a product being collected to go to a recycling process (%)
C_U	Fraction of mass of a product going to component reuse (%)
DAM_d	Indicator result for damage category *d*
E_c	Efficiency of the recycling process used for the portion of product collected for recycling (–)
E_f	Efficiency of the recycling process used to produce recycled feedstock for a product (%)
F_R	Fraction of mass of a product's feedstock from recycled resources (%)
F_U	Fraction of mass of a product's feedstock from reused resources (%)
$F(X)$	Utility factor built as a function of the utility factor X (–)
L	Actual average lifetime of a product (years)
L_{av}	Actual average lifetime of an industry average product of the same type (years)
LCA_T	Normalized and Weighted Results of the LCA (–)
LFI	Linear Flow Index (–)
L_p	Lifespan of a product (years)
L_{sys}	lifespan of an industrial product (years)
MCI	Material Circularity Indicator (%)
MCI_p	Product Level Material Circularity Index (–)
MCI_p^*	Material Circularity Indicator for a product (–)
$M(x)$	Total Mass of the product *x* (kg)
PCI	Product Circularity Indicator (–)
RCP	ReCiPe 2016 aggregated impact factor (Pt/MWh)
W_c	Waste generated to produce recycled content (kg)
W	Waste generated during the recycling process (kg)
W_F	Waste generated during the recycling process (kg)
W_o	Unrecoverable waster amount (kg)
V	Overall virgin component for a product (kg)
$V(x)$	Virgin feedstock for the product *x* (kg)
X_i	Product Utility for product *i* (–)

Greek symbols

δ_d	Normalization factor for damage category *d*
ε_d	Weighting factor for damage category *d*
θ_{ei}	Damage component with respect to the elementary flow *i* impact factor *e*

Abbreviations

CE	Circular Economy
CSP	Concentrating solar power
ESC_i	Environmental Sustainability and Circularity Indicator
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MFA	Material Flow Analysis
PCM	Phase Change Materials
SCSD	Sustainable Circular System Design
TES	Thermal Energy Storage
WMS	Waste Management System

Indices

d	damage category
e	impact factor
i	elementary factor

option to produce clean thermal energy [5]. However, they present a challenge as temporal fluctuations are experienced based on seasonality and daily patterns. However, this challenge can be overcome by integrating energy storage, in this case, thermal energy storage (TES) [6]. The efficiency, as well as the flexibility of thermal solar applications, can be greatly increased with the help of TES systems [7], where the excess energy produced by the system is stored and then used later when the thermal energy is needed [8]. Flexibility between supply and demand can be managed using large scale TES in CSP plants [9]. TES are classified into the following technologies [10]: (1) use of chemical reactions or physical sorption, which is known as thermochemical storage; (2) the use of phase change materials (PCM), which is known as latent heat storage; and (3) the use of the heat stored in liquid media or solid media, which is known as sensible heat storage.

Due to favorable properties such as higher specific heat, lower cost, mechanical properties, and easy processing, concrete is the material often chosen for sensible heat storage at high temperatures [5]. Whereas for the liquid media, materials such as mineral oils, molten salts, and synthetic oils can be used [11]. Due to the density difference between the hot and cold fluids, the material maintains natural thermal stratification. Due to the melting enthalpy, heat can be stored nearly isothermally in some materials using latent heat [12]. According to the temperature range and the application, the correct PCM should be chosen [13]. The correct PCM in each system has to be chosen depending on the application and its working temperature range [14].

According to a recent study by Palacios et al. [10], publications regarding TES have increased exponentially recently. However, most of those publications have neglected the sustainability aspect and have only addressed the technical aspects such as new control, new applications, new enhancement in technologies, and new materials [15]. Following the IEA energy storage roadmap [16], the importance of TES was also highlighted, with a potential for CO_2 emissions reduction estimated to be 2.6 Gt. Furthermore, a recent study shows that TES have a significant environmental impact [17]. One reason for the high impact is the absence of the closing of material loops in addition to the lack of sustainable redesigning concepts for thermal energy storage. Thus, a comprehensive environmental assessment such as a life cycle assessment (LCA) [18] can be a key aspect to fulfil the European legislation [19] regarding the necessary decision support to minimize the environmental burdens associated with the utilization of the TES. Furthermore, technologies in integrated waste management systems (WMS) such as waste treatment technologies and a combination of recycling and reused concept can also be useful in analyzing TES [20]. In this context, Guarino et al. [21] and Abokersh et al. [22,23] examined seasonal TES and its environmental impact in a complete district heating infrastructure. Pelay et al. [24] presented a LCA of a hypothetical tower CSP plant with a Rankine power cycle with thermochemical energy storage (TCES) with calcium hydroxide. The result of the comparison of the LCA with the reference plant without storage concluded that the additional environmental impact due to the TCES system was relatively small. In addition, Gasa et al. [25] proposed a detailed LCA of a CSP tower plant with molten salts storage in a baseload configuration is carried out and compared with a reference CSP plant without storage. While, during the manufacturing and operation phase of the three different TES types for solar power plants, their impact on the environment was compared by Oró et al. [26]. Furthermore, the LCA of two TES designs, namely indirect thermocline and indirect molten salt are compared by Heath et al. [27]. Most of the life cycle assessments of TES systems have focused on the production, operation, as well as the end life as a single value [28]. Thus, all these studies did not focus on environmental analysis due to the potential of recycling and reuse of materials.

Regarding this limitation and to revise the current linear economy with a 'take disposition' model, circular economy (CE) is one of the techniques endorsed by the United Nations Environmental Program (UNEP) and the Ellen MacArthur Foundation for decoupling [29,30]. CE can be defined in large part as an industrial system that is intentionally and in terms of design restorative or regenerative. The Ellen MacArthur Foundation replaces the idea of end-of-life with reorganization and shifts to the use of sustainable resources and to eliminate utilization by a more advanced level of substance, processes, and business designs of chemical pollutants that impact reusability and waste reversion [31]. This substitutes the notion of a deficit with the regenerative framework to differentiate financial growth from the use of new environmental assets. There are numerous definitions of circular economy in the literature. For example, CE can be explained with the help of 10 circular strategies (R0: refuse, R1: rethink, R2: reduce, R3: reuse, R4: repair, R5: refurbish, R6: remanufacture, R7: repurpose, R8: recycle, R9: recover), based on Potting et al. [32]. CE has many links to sustainable development for economic prosperity, social equity, and environmental quality [33]. Globally, circularity can be achieved by implementing a clean cycle strategy which may start by improving material circularity through improving its environmental life cycle [34].

To assess CE, different methodologies have been proposed and applied, most prominently material flow analysis (MFA) and LCA [35,36]. MFA is a tool that helps to understand the flow of a waste management system, as well as it is a starting point of the environmental assessment. Furthermore, MFA reveals opportunities for improving and monitoring the recycling targets [37]. On the other hand, LCA can be used to assess the system environmental performance [26]. However, a complete LCA is laborious and complex as well [38]. Another approach is to use a shortened LCA form, also known as streamlined LCA [39]. Moreover, the project PRO SUITE [40] has presented another approach that takes into account all activities and their effects on the economy, society, and environment. The assessment proposed by them is based on the five pillars, which are (1) impact on exhaustible resources, (2) social well-being, (3) prosperity, (4) natural environment, and (5) human health. However, the sustainability of TES has not been assessed using these methods. Following Cobo et al. [41], other assessment methodologies were proposed to assess CE, including the life cycle costing [42], economic and environmental optimization [43], and the combination of MFA and LCA in multi-objective optimization [44]. Blum et al. [45] suggested an appraisal for all CE activities based on the light of economic, environmental, and social sustainability. Furthermore, Tomić and Schneider [46] tracked each energy vector and calculated coverage of energy needs inside the analyzed systems. This method secures an analysis for the energy recovery of waste to evaluate its circularity. Even though the previously mentioned strategies can be utilized for the appraisal of CE parts of TES, an extensive and organized strategy for the frameworks that grasp CE features while decreasing ecological effects for the TES is lacking.

This study's main novelty is to develop a method for sustainable circular system design (SCSD) that ecologically assesses the sustainability of TES technologies. This approach can be promoted as a solution to support the sustainability market position of renewable energy systems. Furthermore, the developed method can be utilized to increase circularity and the sustainability of those derived measures. TES is included in this new CE approach of considering our actions, as energy is part of the concept. Going ahead, when developing TES and materials, CE principles should be considered. These principles are territorial ecology, "functionality" economy, reuse, second use, recycle, reparation, industrial, eco-design, and valorization. The technique draws from the pool of conceivable outcomes CE offers, minimal ecological damage, material quality aspects, product design considerations, circularity strategies within the production chain (R0-R9), and waste hierarchy.

The developed SCSD methodology will be tested on high-temperature TES technology using a liquid media system with molten salt as a part of a concentrated solar power plant. Furthermore, SCSD embraces the analysis for the most intensive processes within TES technology through proposing the different ecological scenario, including (i) increasing recycling rates, (ii) increasing the reuse rates, and (iii) a combination of both. The paper structure is as follows: A general outline of the SCSD methodology aspects is proposed in section 2; section 3 describes the application of the methodology in a high-temperature TES application; section 4 presents the paper results and their relevant findings; and finally, the results summary and work conclusion are shown in section 5.

2. The sustainable circular system design (SCSD) framework

The proposed methodology framework for evaluating the circularity of TES is illustrated in Fig. 1. The framework is structured in a 3-phases approach for sustainable evaluating of TES. The first phase (A) is mapping the overall waste movements and management procedures through introducing the material flow analysis (MFA) for the TES bill of materials. Besides, it shows the residuals and contaminations need to be considered. Once this evaluation is implemented, the life cycle assessment (LCA) presents the environmental evaluation of the TES materials. In the second phase (B), the circularity metric is proposed to estimate product preservation through recycling and reuse techniques. The second step in-phase (B) is to evaluate the overall sustainability of TES through combining the LCA indicator with the CE index. Finally, the third phase (C) offers a complete analysis for the effect of various scenarios on the TES circularity.

2.1. MFA/LCA assessment

This phase entails the environmental impact of the product (TES), where the proposed MFA/LCA module has been implemented following Haupt et al. [18] guidelines.

2.1.1. Material flow analysis (MFA)

The MFA offers the transfer factors for all residues processes in multiple entities that can be used for LCA calculations. To fabricate an input dependent model of waste management using LCAs, MFA can be used as the base. Knowledge of the transfer coefficients for all treatments (recycling, incineration, and landfilling) permits designing process inventories for arranging and reusing according to the MFA and ensures the preservation of the mass balance in the framework. MFA includes the comprehensive measurement of the content input and output flows into space at a time specified framework. The system in which input flows are equivalent to the output flows in addition to the accretion of substance in the system [47], as illustrated in Fig. 2, is handled as the black box.

MFA starts by establishing the boundaries of time and space. This strategy includes the examined process as an operation in the anthroposphere. The input flows involve all raw resources mined from nature and the domestic extraction (DE). Hidden flows are products not evident from economic records but needed to produce the resource used at the end, for example, earth-removed products

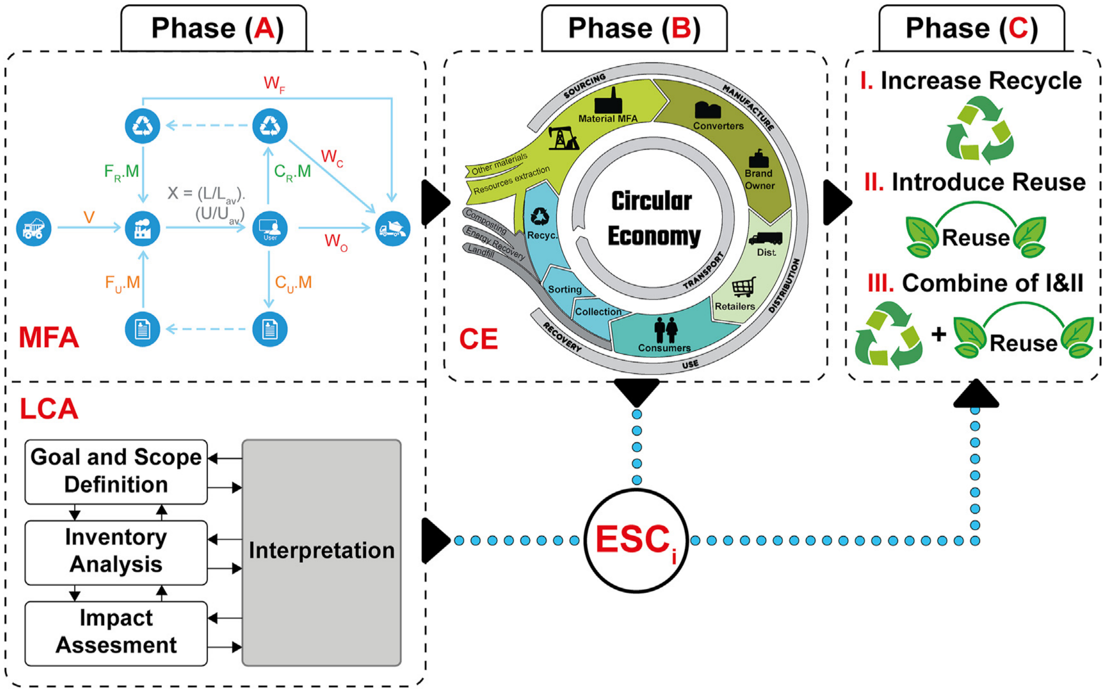

Fig. 1. The SCSD outlines.

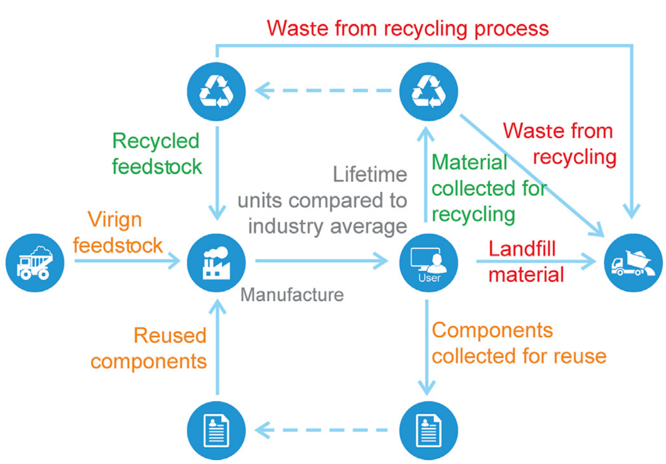

Fig. 2. Schematic representation for MFA [48].

and overburdened mining materials or wood harvest reductions in forestry. Hidden flows, called environmental backpack or “Rucksack”, are measured by means of the Material Intensity per Unit of Service (MIPS) database, given by the Wuppertal Institute [49]. MIPS is a measuring unit designed by the Wuppertal Institute that monitors the material intensity of different products and services with respect to a particular product unit. MIPS measures how products are different from their normal extractions, as Ritthof et al. [50]. All content used is measured in relation to natural resource usages during the production, usage and recovery or disposal. The MIPS definition is based on the perception that the capacity for the product environmental impact can be measured by the Material Input (MI) across its lifespan. Lesser raw materials utilized; lesser environmental impacts faced. As per Ritthof et al. [50], such items have their ecological impact as an intangible "ecological rucksack," i.e. as per the MIPS definition. The eco-backpack can be measured by extracting the product's total weight from the MI (Ecological Backpack = MI-net weight).

2.1.2. Life cycle assessment (LCA)

LCA is a method for the environmental evaluation connected with material, products or operation under which resources, energy and atmosphere (from the cradle to the grave) are defined and quantified [51]. LCA contributes, including the production, utilization, and landfill process, for all resource and energy inputs and outputs of a product over its lifetime. The environmental impact measured by conducting an LCA practice must be transformed into a singular dimensionless value. The proposed procedure includes two sub-processes: standardization and weighting, two additional components of the LCA method of lifecycle impact assessment, as defined in the ISO 14044 International Standard [52]. Standardization is the magnitude measurement for the reference information of the section indicating findings. This will also help convey details on the relative value of the indicator effects [53]. Weighting is a procedure using numerical variables to transform the findings of the impact category metrics, enabling the converted metrics to be aggregated further [54]. LCA intends to examine the unique influence of a product or service on the environmental burdens in its various life cycle phases. The ISO 14040:2006 and ISO 14044:2006 [52,55,56] sets out four interrelated measures: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) interpretation which identifies relevant issues and formulates recommendations. These phases are explained in detail in the next subsections.

a. Goal and scope definition

Three key regions, system borders, and impact groups are included in this process. The whole product development (cradle to grave idea) must be evaluated on the system border. The environmental effects of the impact groups are measured using the ReCiPe 2016 [57] impact value. Eighteen metrics of the middle point effect are chosen and clustered in three groups of endpoint damage. They are classified into three categories: (i) ecosystem quality, (ii) Human health, and (iii) natural resources. These results are given in classifications of impact and by specific measures determine the environmental burden. The ReCiPe is a measure that is broadly utilized for comprehending damage. The decision-maker considers this kind of measure as more comprehensible than the so-called mid-point concept [4].

b. Inventory analysis

It takes into account input, performance, and energy use in connection with product in the second phase of the LCA sequence. In the impact evaluation step, they are further interpreted into waste and pollution. The material distribution and delivery to the factory are regarded during the entire project time. Besides the product effects and the energy usage (natural gas and electricity) in the framework, the product-related reserves have been taken from the Ecoinvent 3.7 directory during its lifespan [58].

c. Impact assessment

The inventory records are transcribed into sustainability reports during this step. As already stated, three separate areas of harm are covered: the environment, health care, and risk to infrastructure centered on the 2016 ReCiPe framework [57]. The assisted system classification may be carried out for the midpoints depending on the endpoints scale. The damage can be represented as follows numerically for each impact section.

$$IMP_e = \sum_i \theta_{ei} \cdot LCI_i^{ToT} \; \forall e \tag{1}$$

where LCI_i^{ToT} is the life cycle inventory related to production, resource logistics and plants execution, correlated with the primary flow i. θ_{ei} showed the damage material with respect to the elementary flow i impact factor e. This aspect encourages a connection between the inventory and the classifications of damage.

$$DAM_d = \sum_{e \in ID_d} IMP_e \; \forall d \tag{2}$$

$$RCP_d = \sum_d \delta_d \varepsilon_d DAM_d \; \forall d \tag{3}$$

where ID_d describes a classification of endpoint effects in damage classification d. RCP is the standardized ReCiPe 2016 measure and δ_d, and ε_d are the specific weight and normalization elements. The normalization element is calculated based on the EU damage computations for land use and emissions calculations [59]. The weighting variables are calculated based on suggested values as described in the ReCiPe 2016 [60].

d. Interpretation

In addition to several suggestions that help improve system efficiency, this step offers an evaluation of the findings. In this sense, policymakers can recognize the weak points conveniently along the way, where additional effort must be made to decrease the environmental impact. Even so, there are no specific boundaries on how the decrease can be achieved. Besides, because of the range of possibilities accessible and differing targets (i.e. impact classifications) in many situations, assessment is highly complicated. The LCA findings can be implemented as variables in the statistical model in order to address these constraints.

2.1.3. MFA/LCA combination

Both MFA and LCA include production, use, and end-of-life of the products within the system, to allow for deriving measures at every step of the life cycle. The functional unit for both MFA and LCA should consider the service the investigated system provides over a determined time span [37]. The direct link between the MFA and the LCA is established through the product-process-matrix proposed by Haupt et al. [18], where each process entails a certain environmental impact.

Combining the MFA and LCA is used to facilitate waste management and provide environmental impact data on multiple mass flow situations. The integration of regional MFA and LCA makes environmental assessment evaluations, thus maintaining continuity between factors such as the transition parameters of MFA and LCA process models considering the capacity constraints on waste management systems and the accessibility of waste resources. Besides, the input reliance on process output and the related environmental impacts may be observed, both for specific waste management processes like urban waste combustion and for alternate materials used as feedstocks.

2.2. Circular economy (CE) assessment

The CE aims to represent the circularity of product consisting of product level Material Circularity Indicator (*MCI*). These structures then comprise a collection of products and materials, including functionality and interlinked behaviour. The 'ideals' of the CE should be correlated to all such metrics; (1) planning of the waste (2) product resilience by variety, (3) dependency on electricity from sustainable resources, (4) thought of "systems," and (5) wastes as fuel, are some of the recommendations that can be followed from comprehensive work carried out by the Ellen MacArthur Foundation [61].

This part concludes the advancement of a circularity evaluation method and the design composition. Part of this assessment is based on the methodological work undertaken on the 'circularity metrics – a guide to the calculation of circularity' by the Ellen MacArthur Foundation and Granta [30]. They established metrics that could be applied to designers as help for implementing choices, along with being utilized to various other ends, including acquisition choices and company assessment rates. The metrics rely mainly on non-renewable sources of technological cycles and resources. Since the research topic does not respond to Ellen MacArthur Foundation & Granta methods, further growth of a product evaluation technique is made.

2.2.1. Assessment methodology design

The *MCI* expresses the amount to which virgin feedstock is minimized, and, as contrasted to a similar industrially average product [62]. The *MCI* consists fundamentally of three main features: (1) mass of virgin raw materials used in the manufacturing phase, (2) mass of unrecoverable waste assigned to this product, and (3) utility factor, which represents the duration and severity of *MCI* usage of this product. Fig. 2 describes the numerous *MCI* parameters.

MCI_p is the fundamental step towards the product level material. A product *MCI* can be classified by taking into consideration the product linear flow index (*LFI*) and the factor $F(X)$, which is constructed as a function F of the utility X, which decides the impact of the product utility on its *MCI*. The formula of Ellen MacArthur and Granta [48] used for measuring the *MCI* for a material is:

$$MCI_P^* = 1 - LFI \cdot F(X) \tag{4}$$

$$MCI_p = max\{0|MCI_P^*\} \quad (5)$$

2.2.2. Formulating product circulatory metric

The Ellen MacArthur Foundation & Granta [48] evaluation process is the guiding principle. The CE tests the degree to which linear flows have been reduced, and restoration flows amplified and how frequently and rigorously it is utilized contrasted with a comparable system-average product. The concept behind the CE is to analyze the application, features and outcomes. The materials and products and the linkages, and the assembly of the structure should be taken into account in the implementation of the CE independently. Products and materials are recovered in the market in technical intervals to the best appropriate standard and by replacements, maintenance, reuse, restoration, analysis, and recycle for as long as feasible. However, non-toxic materials in a wide range of applications are preserved. The development of CE is confined to the material's technology process. The organic process is not considered because the evaluation of this period is entirely different.

In developing the evaluation model, the first step is to develop a product level material circularity indicator (*MCI*) by evaluating the product's input, output, and effectiveness. The "theoretical" circularity attribute for a system without configurations and only the product itself may also be represented. The *MCI* will finally produce an *MCI* for a product for each material assessment. The input and output of materials include the content of virgin or non-virgin materials and then reusable or non-reusable materials.

2.2.3. Material circularity indicator (MCI)

The *MCI* for a product depends on the assumption that construction is an ensemble of materials attached in a particular manner where every product has its circularity and characteristics. The basic principle for circularity is 100% non-virgin content at end-of-life and 100% recycled. The *MCI* for a product measures the degree the linear flow has been mitigated, the restorative flow of basic elements amplified, and how much longer (often an estimate) the item is used, particularly in comparison to the systemic layer valuation the construct [62].

The *MCI* is mainly focused on the following features (see also Fig. 3):

- Mass of virgin feedstock content in development.
- Mass of waste that is recognized as unrecoverable after the operation.
- The utility factor *X* with the item's lifespan/functional value.

These features are mainly utilized to calculate the Linear Flow Index and the Material Circularity Indicator (MCI_p).

For the determination of *MCI*, a differentiation between a fully linear product and a complete 100% circular product should be considered. From a single product perspective, it is considered a linear product when 100% of the virgin feedstock goes to the landfill. Furthermore, it is considered as a circular product when 100% non-virgin feedstock is utilized. All cumulative effects may be derived from this differentiation as an inference, which are the two extremes of *MCI* within a spectrum [0, 1], from 0% (linear) and 100% (circular).

In order to evaluate MCI_p as part of the final product, various materials are required to be evaluated using comprehensive information of parts and specifications in a product. Thus, it is critical that the bill of material is a complete and fully accurate material breakup. The MCI_p is established first by analyzing the input and output of the material and then by analyzing the utility factor of the product.

The amounts 'linear flow index' and 'material circularity measure' are successively explored in evaluating the products input, material performance, and utility factor.

a. Determination of the material input

As previously stated, there was a difference between virgin (raw material) or non-virgin (reused, revamped, repaired or rehabilitated) material production. All materials that are a part of a product may be applied to a production process, by Virgin Feedstock, Non-Virgin Feedstock, Fraction Recycled materials, and Fraction Remanufactured materials. A product is then produced with a variety of parts: subassemblies, sections and/or materials. A Bill of material can define all materials centered on the scale of specifics. The Material Circularity Indicator can summarize all materials input predicated on all subassemblies, elements, and/or materials (x).

The virgin materials feedstock is presented for every assembly, portion and/or material (x):

$$V(x) = M(x)(1 - NV_{RC(x)}) \quad (6)$$

where $V(x)$ is a portion of virgin feedstock for each manufacturing process, $M(x)$ is the whole assembly mass, $NV_{RC(x)}$ is the feedstock component for each assembly from the non-virgin material.

The quantity of all distinct subsystems, materials or raw materials are the overall virgin component for a product (V):

$$V = \sum_x V(x) \quad (7)$$

If the Virgin Feedstock is equivalent to zero, the entire intake comes from a material that has a full circular input.

b. material performance evaluation

The material output is the target after the lifetime of the product. Again, the products reusable portion is the maximum amount of resources found for a second, a third or at least a next life without distinguishing between the reused, renovated, remanufactured and recycled item. The other alternative is to use it to produce energy or to detect when it is unable to consider taking the next lifespan.

A differentiation between the reusable percentage and the waste should be taken in this situation. The recovery of resources and/or deposition is then known as waste, and the other proportion is seen to be reusable. The waste (W) in an incinerator (energy recovery) or goes to the landfill can be expressed as:

$$W = W_O + \frac{W_C + W_F}{2} \quad (8)$$

where W_O is the unrecoverable waster amount, W_C waste generated to produce recycled content, and W_F is the waste generated during the recycling process. When the waste (W) is equivalent to 0, then it offers all materials a subsequent existence (second or subsequent existence), implying a circular output.

c. The material utility factor

The utility of a product is related to the materials and the product lifetime. The period of the product use phase (L_P) is the lifespan of a product. The period aspect reflects any decline (or increase) in waste streams for products that have a prolonged (or shorter) life cycle than certain products from various manufacturers over a given number of years. If a product lifespan is doubled,

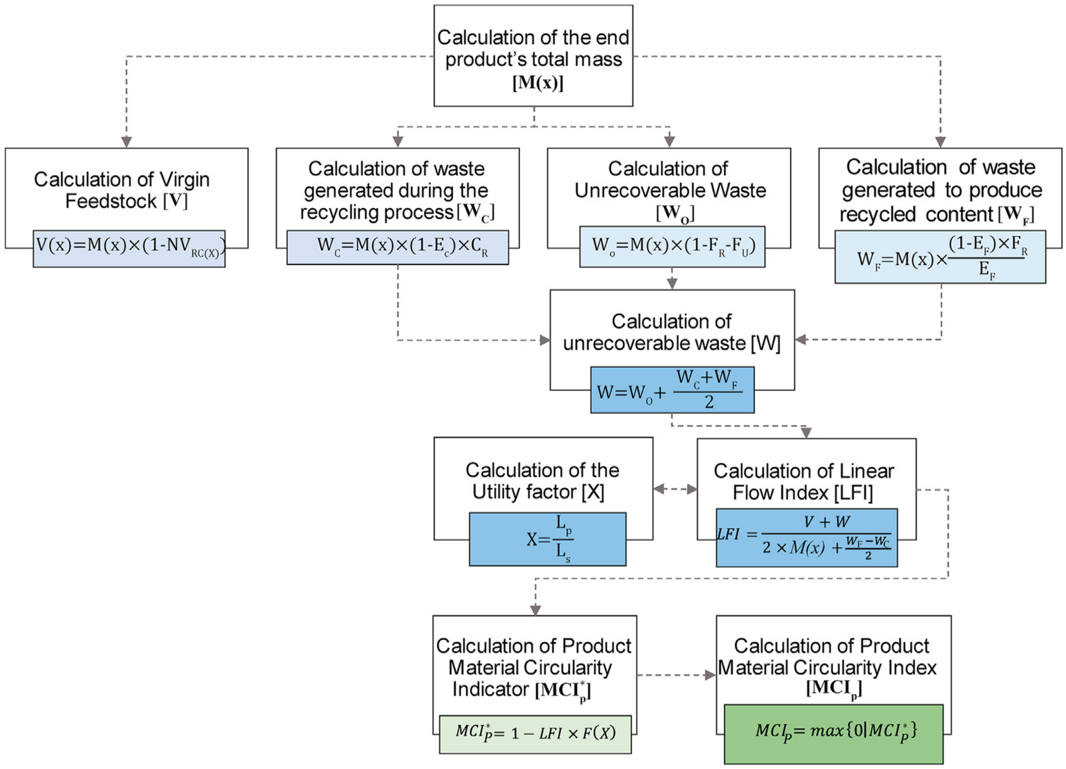

Fig. 3. The material circularity indicator (*MCI*) Workflow [63].

waste is generated, and the virgin materials used every year are cut in half. The secondary element is the (L_{sys}) which is linked to the industrial lifespan of an industrial product. The determination of the X utility can be done as:

$$X = \frac{L_P}{L_{sys}} \tag{9}$$

This means that if a product lifetime (L_P) is extended, a beneficial effect can be reflected in the utility. It is necessary to bring the product into perspective and to be part of a system that is either intensively or insufficiently utilized in the event of request adjustments (end of the deal or 'only' shifting requirements), and the ties to other products. A substance produced for excessive lives (utility X is significant), which ends up as energy rehabilitation or landfill, is not a circular but instead a gradual linear operation. There seems to be a debate between environmentally-efficiency and eco-effectiveness. Consequently, eco-efficiency, which reduces the need for resources, has a constructive significance for this highlighted scenario compared to eco-efficiency, which has a negative connotation (to do good instead of less). The aim of eco-effectiveness is not to reduce the flow of material from cradle to grave, but to create cradle-to-cradle metabolisms that allow materials to sustain their role as a resource. The connection between economy and ecology is, therefore, strengthened in a positive way. This tool could include either eco-efficient or eco-effective collectively with productivity, based on the prerequisites. The presumption of the highest longevity in good materials is the best option.

d. The linear flow index

The Linear Flow Index (*LFI*) stands for the portion of materials that have a linear flow where 100% of the virgin stock feed goes to the landfill or energy recovery units at the end of the material lifetime, and it can be expressed as follows:

$$LFI = \frac{(V + W)}{2M(x) + \frac{W_F - W_C}{2}} \tag{10}$$

If all the products are reused, remanufactured and/or recycled, the *LFI* is in the reverse direction, and the entire path is circular.

e. Determination of the material circularity indicator

By evaluating the input, value and performance, the material circularity measure of material can now be calculated. The *MCI* is established for a product:

$$MCI_P^* = 1 - LFI \cdot F(X) \tag{11}$$

where, LFI_P is the Linear Flow Index (from the Virgin Feedstock and Waste), $F(X)$ is the function of the utility factor X.

$$F(X) = \frac{a}{X} \tag{12}$$

where:$F(X) = \frac{a}{X}$with a is a constant

Ellen MacArthur Foundation [48] established a = 0.9. Accordingly, the usefulness of a product (e.g. through longer use) affects the *MCI* as it does reuse of materials which, in an amount of time (eco-efficiency), result to an equal amount of reduced virgin material use and waste not retrieved.

2.2.4. Development of the environmental sustainability and circularity assessment indicator

The final phase is the interpretation of sustainability through combining their overall circularity and environmental impact. The circularity of the product is not taken into account in the LCA structure, and the *MCI* quantification structure does not take into account the ecological consequences of the respective manufacturing process. As already stated, efforts to increase the circularity of product may ultimately have negative environmental impacts; and efforts to mitigate the ecological consequences of the developed product may, theoretically, contribute to a decline in circularity. Therefore, an index indicator is normalized and aggregated effects of the LCA as its base value (LCA_T) at the power of the value (1-MCI_p). Below you can find the equation defining the index [63]:

$$ESC_i = \frac{1}{LCA_T^{\,(1-MCI_p)}} \times 100 \tag{13}$$

The environmental effect of the analyzed product and its material index must be measured in order to measure the Environmental Sustainability and Circularity Indicator as defined over the last sections. Consequently, in terms of sustainable development and circularity, this technique can be used to grade the alternative options of a certain product. *ESC* is various from 0% to 100% where the higher *ESC* value, the better it is contrasted with the lower-ranking indicators. An important factor of *ESC* is that it follows the same system borders for either type of evaluation, environmental sustainability and circularity. It is an essential factor that requires all tests to be combined into a single metric.

2.3. Development of scenarios

Following the SCDS approach for assessing the product technologies circularity based on using the MFA/LCA in the first phase and the CE in the second phase, three future scenarios were proposed and compared to the current product circularity situation (baseline scenario) to complete the SCDS approach. These scenarios can highlight the possible improvement potential in the WMS, including increasing the recycling and reuse rates in order to create new treatment pathways. It is important to keep in mind that the developed scenarios are ordered based on the level of required changes where the third scenario would introduce radical changes in the WMS, whereas other scenarios can present changes which can be attained in the near future.

2.3.1. Increase recycle rates scenario (Modest Scenario)

Due to the current low circularity for the TES materials, an option to increase recycling is proposed as an initiation to support the sustainable deployment for TES technologies in the near future. In the scenario, all materials entered the closed-loop recycling pathways where the recycling rates of the most relative environmental impact materials in TES technologies is increased by 70%, following the EU 2030 target for waste management [64].

2.3.2. Increase low impact material use (Medium Scenario)

In the reuse increment rates scenario, we would propose the EU 2030 targets of increasing the reuse rates of relative materials by 30%. This scenario can contribute to the reduction in TES raw materials extraction and subsequently increase its circularity. The selection of the reuse construction materials and their relative reuse efficiency is shown in the case study section.

2.3.3. Optimistic scenario

In the third scenario, we propose a combination of the two previous scenarios where the recycling rates are increased by 70% in parallel with the reuse concept to contribute toward the EU 2030 targets. This scenario preserves an ambitious scenario where radical changes in climate change and human toxicity impacts can be reached by improving the current WMS situation.

3. SCSD application — TES cases studies

This paper demonstrates the developed approach by an application to high-temperature TES technology as a part of concentrated solar power plant. This TES have been employed from the literature; this case has been built in a pilot plant scale at Andasol, Spain [65], as shown in Fig. 4. The functional unit for both the LCA and circularity assessment will be carried out per kWh of storage material. The proposed TES technologies used $NaNO_3$ and KNO_3 based molten salts to store sensible heat in the system [12].

3.1. Liquid media system description

This article is based on the thermal storage system in the research performed by Gabbrielli et al. [66]. This project is proposed as an upgrade in their conventional parabolic trough commercial plants.

The proposed Solar TES consists of two molten salt storage tanks. The first storage (Hot Tank) holds the salt at a high temperature up to 388 °C, whereas the other storage (Cold Tank) holds the salt at a low temperature of 288 °C. Both tanks are identical in dimension and shape identical to avoid complexity. These tanks have a cylindrical shape with a diameter of 22.4 m and a height of 11 m. The volume of each tank is around 4335 m^3 as it needed to store 5500 tons of molten salt to store 600 MWh_{th}.

As shown in Fig. 5, the molten salt storage tanks are constructed into different layers. For the lateral walls (inside out): A stainless steel flexible protective liner is used, next is insulating firebricks' layer, a carbon steel made tank shell, an insulating layer of ceramic fiber, exterior insulation of ceramic fiber, and an aluminum sheet. The tank bottom also has different layers, a stainless steel flexible protective liner, a layer of insulating firebricks, carbon steel tank shell, fine sand, insulating firebricks, foamglas®, reinforced concrete with a water-based cooling system, poor concrete, and foundation piles. The tank roof is also made up of different materials: a stainless steel flexible protective liner, ceramic fiber insulation, ellipsoid-shaped carbon steel sheet, and ceramic insulating material. The main characteristics of these storage tanks are shown in Table 1.

Several equipment are required in the TES, where each molten salt tank is connected to an electric pump in addition to water cooling and heating systems. The temperature of the concrete base is maintained below 100 °C through the water-cooling system. While the salt solidification is prevented through the heating system. Furthermore, molten salts pumps are installed to transfer the salts between the hot and cold tanks.

3.2. LCA and CE input data

The proposed methodology application is illustrated through the molten salt TES where its material inventory is shown in Table 2. Based on the proposed approach, the LCA includes the production, utilization, recycling, and landfill process, for all resource and energy inputs and outputs of a TES over its lifetime. The LCA data were retrieved from the Ecoinvent 3.7 database [68]. This database comprises the production, recycling and disposal stages of the proposed TES based on the ReCiPe 2016 methodology.

A summary for the total normalized damage categories of the TES comprising three main stages: (i) material market, (ii) recycled waste market, and (iii) disposal waste market is shown in Table 3 where no data is found regarding the recycling of molten salt as well as firebricks, ceramic fibre, sand and foamglas. Moreover, the CE of molten salt storage is estimated based on counting for the

Fig. 4. A molten salt TES pilot plant located in Seville (Spain) [65].

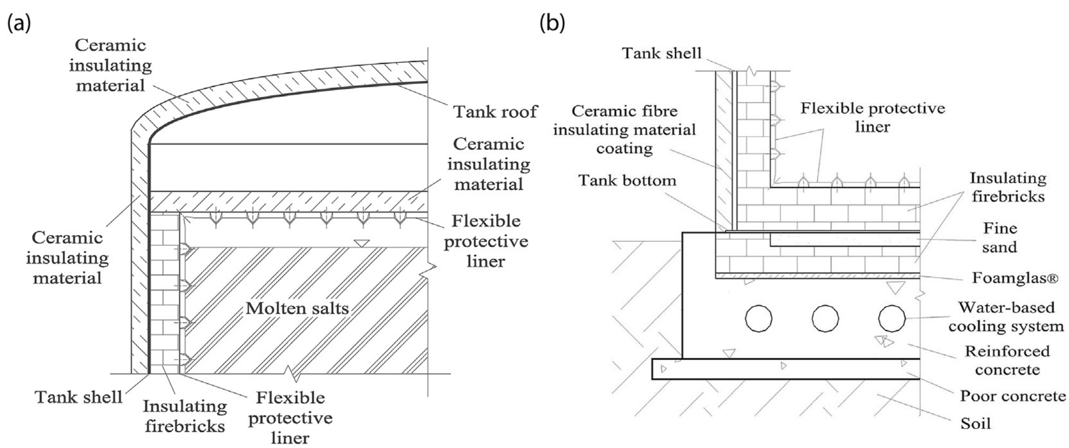

Fig. 5. A cross-section for the molten salts storage tank where:(a) roof & (b) construction base [67].

Table 1
The molten salt storage tanks characteristics [26].

	Units	Value
Diameter	m	22.4
Height	m	11
Storage unit volume	m^3	4335
Weight of steel	t	279
Lantern material insulation thickness	mm	125
Roof insulating thickness	mm	125
Foamglas® thickness	mm	40
Number of brick foundation	–	2
Number of brick vessel	–	1
Number of brick bottom	–	5

Table 2
Material inventory during the manufacturing phase in the liquid media system [65].

Component	Units	Material Used
KNO_3	kg	3,300,000
$NaNO_3$	kg	2,200,000
Concrete	m^3	551.71
Poor Concrete	m^3	236.45
Sheet metal	m^2	3360.95
Firebricks	kg	1,271,756.92
Carbon steel	kg	554,052.81
Ceramic fibre	kg	10419.79
Aluminum sheet	m^2	1548.18
Sand	kg	417,726.27
Foamglas	kg	4256.08

recycling and reuse rates in addition to their relative efficiency. Following Boer et al. [38], the value of recycled content and their relative efficiency in molten salt storage varies between different materials inventory. On the other hand, with the lag of data regarding the reuse concept in the molten salt material inventory, we excluded from reuse from the initial scenario calculations. Table 4 shows a summary for the recycling rates of the TES material inventory, which are extracted from CES Selector 2018 [69], whereas their relative efficiency is following the estimated values in Verberne work [62].

Table 3
Total environmental life cycle impact at different life stages for molten salt TES represented in ReCiPe points (Pt) per characteristic dimension [68].

Component	Unit	Material stage		
		Material market	Recycled waste market	Waste final disposal
KNO_3	(Pt./kg)	0.38	–	0.0025
$NaNO_3$	(Pt./kg)	0.73	–	0.0025
Concrete	(Pt./m^3)	47.49	1.71	2.99
Poor Concrete	(Pt./m^3)	43.00	1.71	2.99
Sheet metal	(Pt./m^2)	0.36	0.01	0.001
Firebricks	(Pt./kg)	0.15	–	0.06
Carbon steel	(Pt./kg)	0.14	0.01	0.001
Ceramic fibre	(Pt./kg)	0.08	–	0.03
Aluminum sheet	(Pt./m^2)	0.62	0.02	0.01
Sand	(Pt./kg)	0.01	–	0.001
Foamglas	(Pt./kg)	0.45	–	0.01

Table 4
The current recycling rates and their relative efficiency of the molten salt TES material inventory.

Component	Recycling rate in current supply (%) [69]	Recycling efficiency (%) [62]
KNO_3	–	–
$NaNO_3$	–	–
Concrete	13%	90%
Poor Concrete	13%	90%
Sheet metal	39.9%	77.8%
Firebricks	–	–
Carbon steel	39.9%	77.8%
Ceramic fibre	16.5%	77.8%
Aluminum sheet	52.3%	77.8%
Sand	–	–
Foamglas	–	–

4. Results and discussion

4.1. Life cycle inventory

The life cycle inventory of the studied liquid (molten salts) thermal storage media per three damage categories (i) ecosystem quality, (ii) human health, and (iii) natural resources is detailed in Fig. 6. Furthermore, Table 5 lists the calculated total environmental impact of the three material stages, including material market, recycled waste market, and waste final disposal in point per kilowatt-hour (Pt./kWh). As shown in Fig. 6 and Table 5, the material market contributes to the highest portion of the total impact per whole life cycle of the system studied (5.27 Pt./kWh out of 5.53 Pt./kWh, accounting for 95% of the total environmental impact). According to the overall endpoint results, as indicated in Table 5, the human health impacts receive greater consideration than natural resources and ecological impacts (59%).

As shown in Fig. 6, the storage material, which is a mix of two molten salts ($NaNO_3$ and KNO_3), represents the highest impact on all three separate areas of damage as of human health, the environment, and risk to the natural resources, accounting for 83%, 89%, and 82% of the total impact, respectively. In general, 86% of the total impact is generated by the storage material, followed by firebricks and carbon steel, accounting for 8% and 2% of the overall impact, respectively. The impact received from all other materials is less than 4%, being most of them insignificant. These differences in the impact between the salts and other system materials are due to the high amount of storage material used (5500 ton). This observation implies that the main way to reduce overall impact would be to find more environmentally friendly materials to be substituted with these storage materials.

Fig. 6 also depicts that firebrick and aluminium sheets are the main contributors to the environmental impacts coming from waste final disposal and recycled waste market, respectively. These are related to the high mass of firebrick used (1272 ton) with its high disposal rate, while the aluminium exhibits higher recyclability, thus representing higher environmental impact originated from its recycled waste market.

Fig. 7 illustrates the LCA breakdown for all material stages, including different damage category where the panel (a, d, and g) are depicted for the material market stage, while the recycle waste market stage is shown in panel (b, e, and h) and the final waste disposal is shown in panel (c, f, and i). As described in Section 3.2, the required inputs for quantifying the recycling of molten salts, firebricks, sand, and foamglas were not available, and therefore, there is no evaluation reported for their recycled waste market. Concerning the damage of different materials stages on the eight ecosystem quality categories considered in this study (panels a, b, and c), the natural land transformation and the climate change-ecosystems are affected more than the rest of the LCA impact categories.

Among different impact categories in human health damage area (Fig. 7 - panels d, e, and f), human toxicity and climate change-human are the main affected ones. In case of damages on the resources (Fig. 7 - panels g, h, and I), the material impact on endpoint categories varies for each material, however, the fossil depletion is dominant for the material market as well as, namely, the end of life (disposal and recycling).

According to Table 5, there is a substantial contribution from the molten salts affecting the human health damage area (52% of the overall LCA scores). This implies that human toxicity (i.e. emissions to soil, water, and air of substances that harm human health) and climate change-human health (i.e. emissions of greenhouse gases that cause an increase in temperature of the lower atmospheric

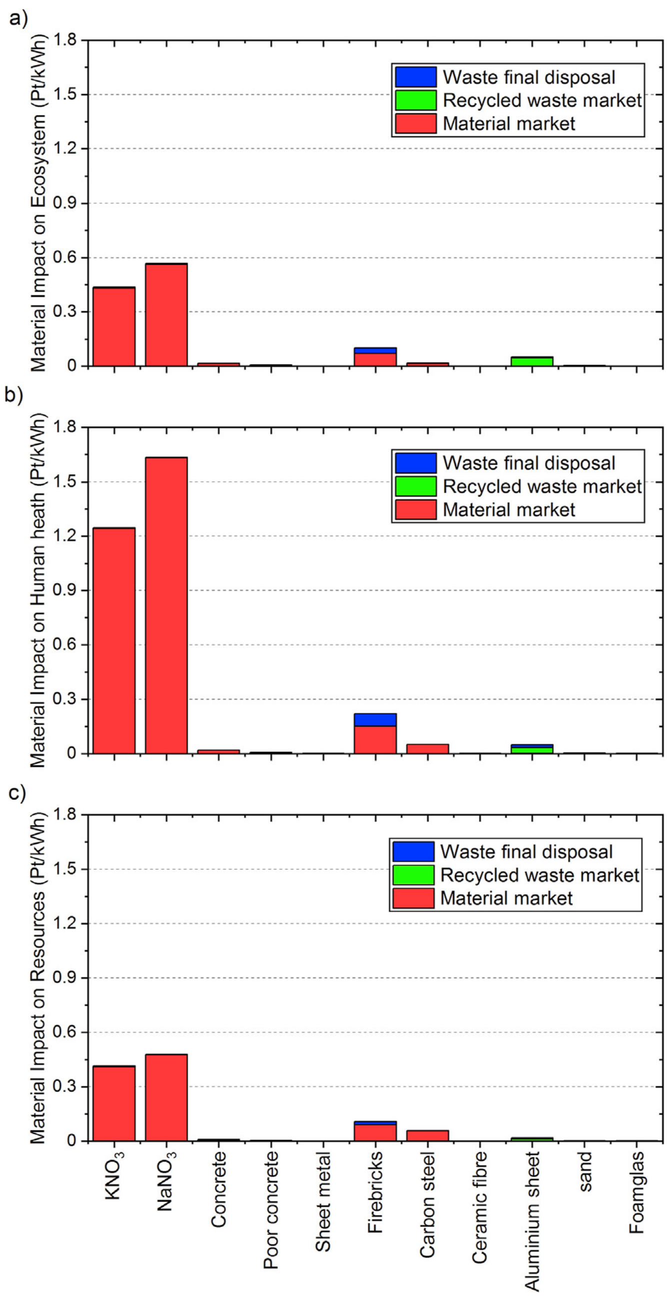

Fig. 6. The complete LCA for the TES with a capacity of 600 MWh. It includes the three damage categories:(a) ecosystem quality, (b) human health, and (c) resources normalized to the storage capacity.

layers with impact on human health) should be considered as the main two impact categories affected by molten salts TES systems.

4.2. MCI/ESC Assessment

Fig. 8 shows the TES materials Sustainable Circular System Design (SCSD) indicators, including the product Material Circularity Index (*MCI*) and the Environmental Sustainability and Circularity indicator (*ESC*). Again, since no data was available on the recycling of molten salts ($NaNO_3$ and KNO_3), foamglas, sand, and firebrick, there are no data reported in panel (a) of Fig. 8. The level of *MCI*, ranging from 0% for the fully linear product to 100% for a fully circular product, which expresses the amount to which virgin feedstock is minimized as contrasted to a similar industrially average product [62]. The higher value of *MCI*, the higher level of circularity potential of the end-product is. Generally speaking, as shown in panel (a) of Fig. 8, currently the circularity of the TES materials is low (less than 50%). Among materials, metallic elements including aluminium sheet, stainless steel (sheet metal), and carbon steel, exhibit higher *MCI* than those reported for non-metallic materials. This is as to be expected since metallic materials are more favorable for recycling.

The value of *ESC* serves as an indicator to evaluate the integration of combined circularity (using *MCI*) and environmental sustainability (i.e. LCA scores) under a closed-loop product system perspective. As depicted in panel (b) of Fig. 8, the stainless steel (metal sheets), ceramic fibre, and aluminium sheets exhibit the top three highest ESCs (1.21%, 0.42%, and 0.26%, respectively), representing the most environmentally sustainable and circular materials among all investigated ones. This is due to the low environmental impacts in the case of stainless steel and ceramic fibre and relatively high *MCI* for the case of aluminum sheets.

4.3. The EU 2030 waste management scenarios analysis

4.3.1. Increase recycle rates scenario (Modest Scenario)

Fig. 4 shows the effect of increasing recycling rates by 70% on the SDCS indicators (e.g. *MCI* and *ESC*) of the investigated TES materials, following the EU 2030 target for waste management [64]. In this figure, those materials with missing data are the items with no data available on their circularity potential.

Increasing the recycling rate enhances the component circularity. As illustrated in Fig. 9 (panel a), the TES system modeled in this study exhibits a Material Circularity Index of 20.6% at the current situation, which can be escalated to 30.3% when the measures proposed by the Modest Scenario are implemented. Aluminium sheets, carbon steel, and stainless steel (sheet metal) are the materials with the highest circularity. The reason behind this is that, as previously noted, aluminium -and metals in general- have high recycling potential as they can be recycled with very low loss of quality along with high energy saving in comparing to the primary production (for example, for recycling aluminium, only 5% of the energy needed for primary production is needed).

Concerning the Environmental Sustainability and Circularity assessment indicator (*ESC*), the current situation represents an *ESC* of 0.23%, while Scenario S1 suggests reaching 1.20% (Fig. 4, panel b). An increase in the recycling rates not only improves the circularity of the system but also decreases the total environmental impacts through reducing material disposal. Consequently, according to

Table 5
Total impact of TES per material and lifecycle stage based on ReCiPe 2016 in Pt./kWh.

	Ecosystem quality	Human health	Resources	Total per lifecycle stage
Material market	1.11	3.11	1.04	5.27
Recycled waste market	0.05	0.03	0.01	0.09
Waste final disposal	0.05	0.09	0.03	0.18
Total per material stage	1.21	3.24	1.09	5.53

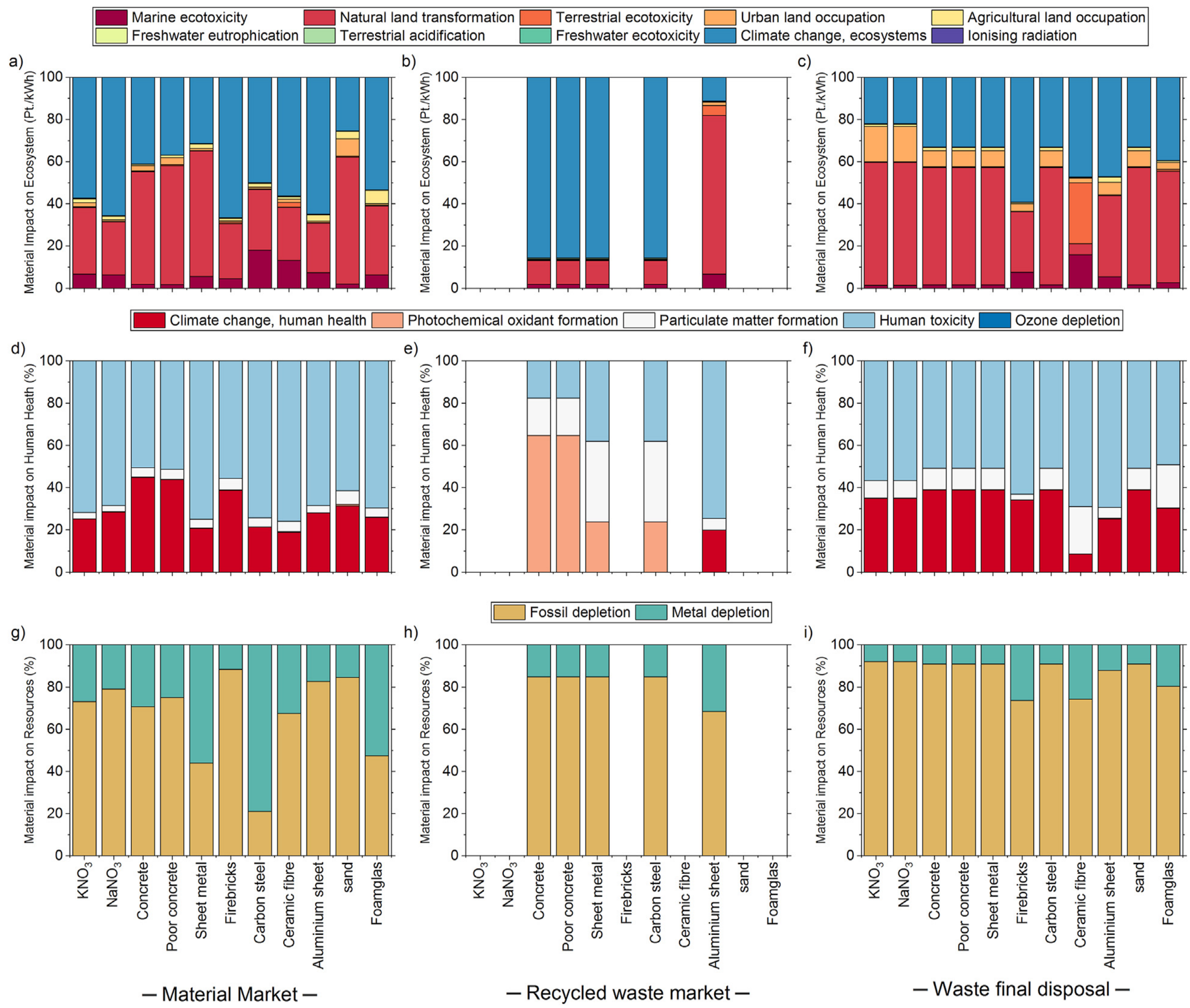

Fig. 7. LCA breakdown for the three material stages including the material market, the recycle waste market and the waste final disposal.

Equation (13), *ESC* is improved for each material, and thus the overall *ESC* increases accordingly.

4.3.2. Increase reuse rate scenario (Medium Scenario)

Fig. 10 depicts the effect of increasing the reuse rates by 30% in the Medium Scenario, following the EU 2030 target for waste management, on the SDCS indicators. Increasing the reuse rates of components and materials would increase the circularity of the system. As shown in Fig. 10 (panel a), the *MCI* of all materials as well as the overall system *MCI* of the Medium Scenario, are increased to a larger extent than the Modest Scenario, showing a higher circulatory improvement.

Moreover, comparing panels (b) of Figs. 9 and 10, it can be seen that the composite indicator of Environmental Sustainability and Circularity (*ESC*) is higher in the case of Medium Scenario by 8.3%. In other words, the introduction of fewer virgin materials into the production system (by increasing reuse rate, as in the Medium Scenario) can be more effective than decreasing disposal waste (by increasing recycling, as in Modest Scenario) from both the circularity point of view as well as the overall environmental impacts, accordingly, resulting to a more environmentally sustainable and circular outcome (i.e., *ESC*) in the Medium Scenario. This limited overall improvement compared to Modest Scenario is due to the absence reuse for the molten salts ($NaNO_3$ & KNO_3), which have the highest environmental impact.

4.3.3. Increase recycle/reuse rates scenario (optimistic scenario)

Fig. 11 depicts the effect of increasing simultaneously the recycling rates by 70% (i.e., Modest scenario) and the reuse rates by 30% (i.e., Medium scenario) on the SDCS indicators. As expected and is also shown in Fig. 11, a higher *MCI* can be reached in this scenario rather than Modest and Medium scenarios. Moreover, the changes to be applied to the current waste management systems (WMS) and the circular flow of the materials, leads to a noticeable increase in *ESC*, by 30 times compared to the current situation. Thus, Optimistic scenario represents the most environmentally sustainable and circular scenario among all the investigated ones. However, this scenario should be considered as an optimistic case since the implementation of this scenario requires applying radical changes to the current waste management system.

5. Conclusions

Conceptually, circular economy (CE) suggests that environmental pressures are closely related to material use, and to reduce the environmental pressures, it is required to circulate and use the

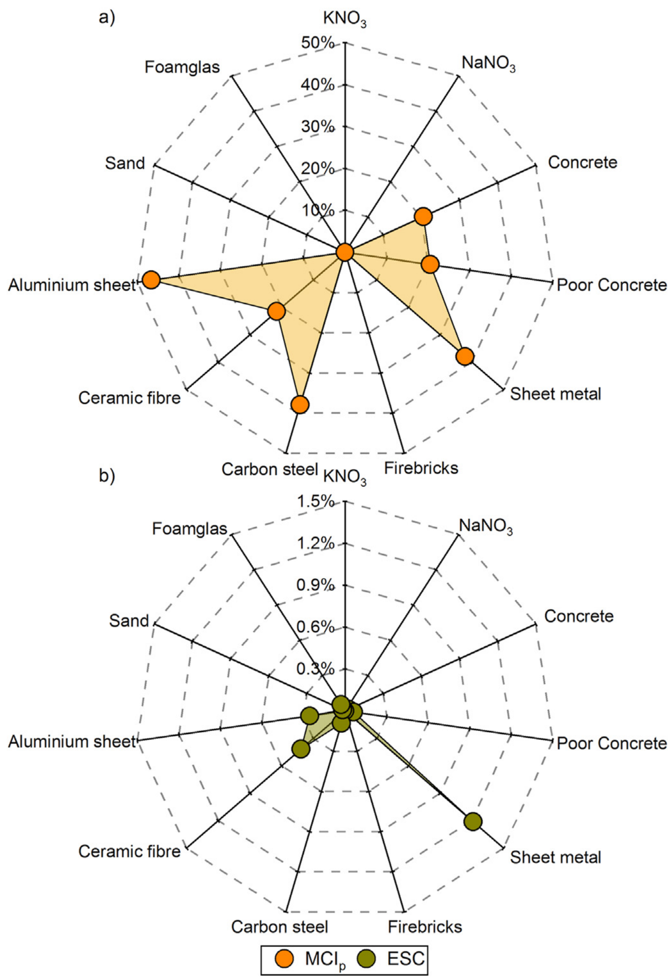

Fig. 8. The TES material SDSC indicators where (a) the material inventory circularity indicator (*MCI*) and (b) the combined environmental impact and circularity indicator (*ESC*).

materials efficiently in the system life cycle. However, it is a proven fact that CE activities do not necessarily contribute to decreased environmental pressures. Therefore, there is a need to consider a methodology that includes the key environmental flows to assess the contribution of CE to environmental sustainability.

In this paper, an extensive and organized strategy for the plan of frameworks that grasps the features of CE, while decreasing the ecological effects of high temperature thermal energy storage (TES) as a part of a concentrated solar power plant was developed. In doing so, an indicator that is defined as a relationship between the aggregated environmental impacts of the “cradle-to-grave” life cycle stage of TES and their product level Material Circularity Index was utilized. To test the proposed methodology, three scenarios have been analyzed: (Modest scenario) increasing recycling rates by 70%; (Medium Scenario) increasing the reuse rates by 30%; and (Optimistic scenario) a combination of both scenarios Modest and Medium scenarios.

The circularity analysis showed that by increasing the recycling at the end of life (Modest scenario), increasing reuse rate leading to less use of virgin materials (Medium Scenario), and a combination of both (Optimistic scenario), the Material Circularity Index (*MCI*) moves from 20.6% for the current situation to 30.3%, 38.6%, and 46.4%, respectively. The results reveal that improving circularity generally reduces environmental impacts from the current situation by 15%, 18%, and 23% for Modest, Medium, and Optimistic scenarios, respectively.

The findings showed that the optimistic scenario represents the most environmentally sustainable and circular alternative with the *ESC* of 7.89%, where Modest and Medium scenarios exhibit *ESC* of 1.20% and 2.16%, respectively. For this specific case study, these *ESC* results emphasize that achieving a CE goes beyond increasing reuse and recycling, particularly considering that to implement the most optimistic scenario, it is required to introduce radical changes in the waste management system. The major obstacles for a substantial increase of *ESC* is the extremely high share of noncircular materials, here the molten salts, accounting for 86% of overall LCA scores. Therefore, any effort to improve the circulatory and the environmental benefits of this TES system should be reached by using more environmentally friendly materials for storage material or attempt to enhance the circularity of the molten salt.

As a general concluding remark, the joint interpretation of *MCI* and LCA scores carried out using *ESC* indicator can provide a more appropriate ranking factor than evaluating environmental impacts and the level of circulatory of the products individually. This work also suggests that the integration of reusing and recycling at the initial design should be considered in order to achieve a more environmentally sustainable and circular result.

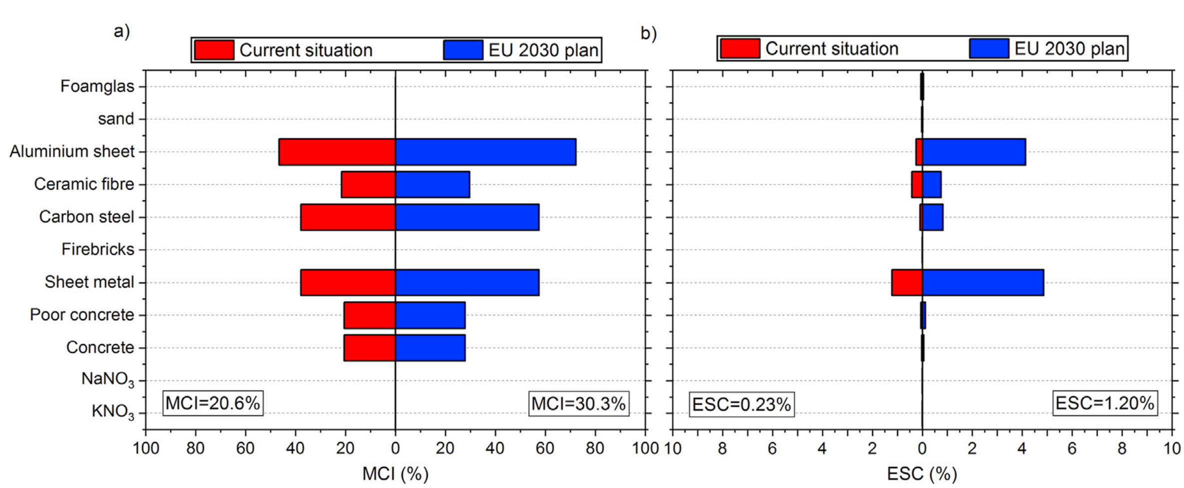

Fig. 9. The effect of increasing recycling rates by 70% on SDCS indicators where (a) *MCI* indicator and (b) *ESC* indicator.

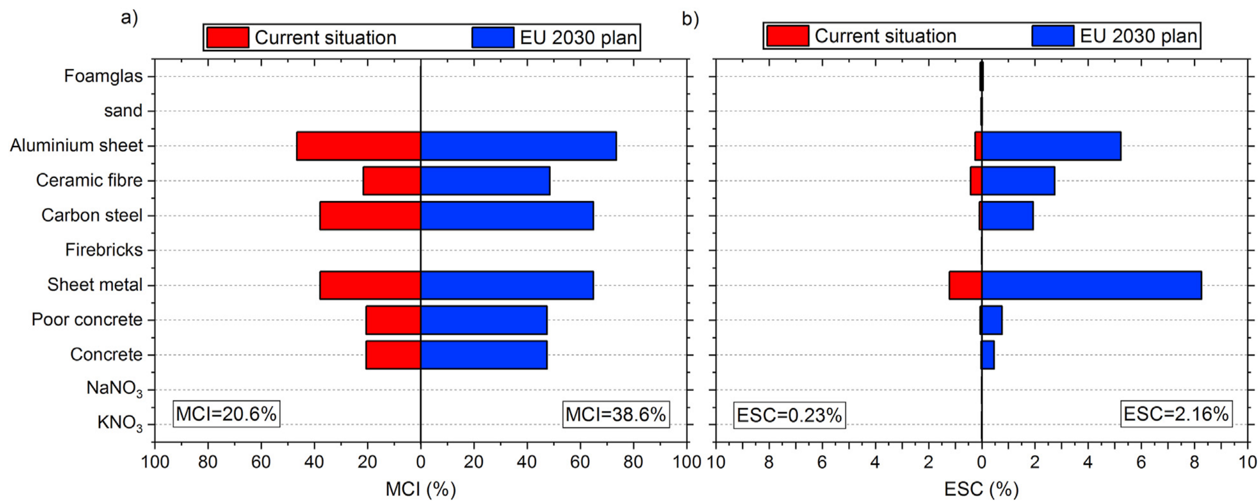

Fig. 10. The effect of increasing reuse rates by 30% on SDCS indicators where (a) *MCI* indicator and (b) *ESC* indicator.

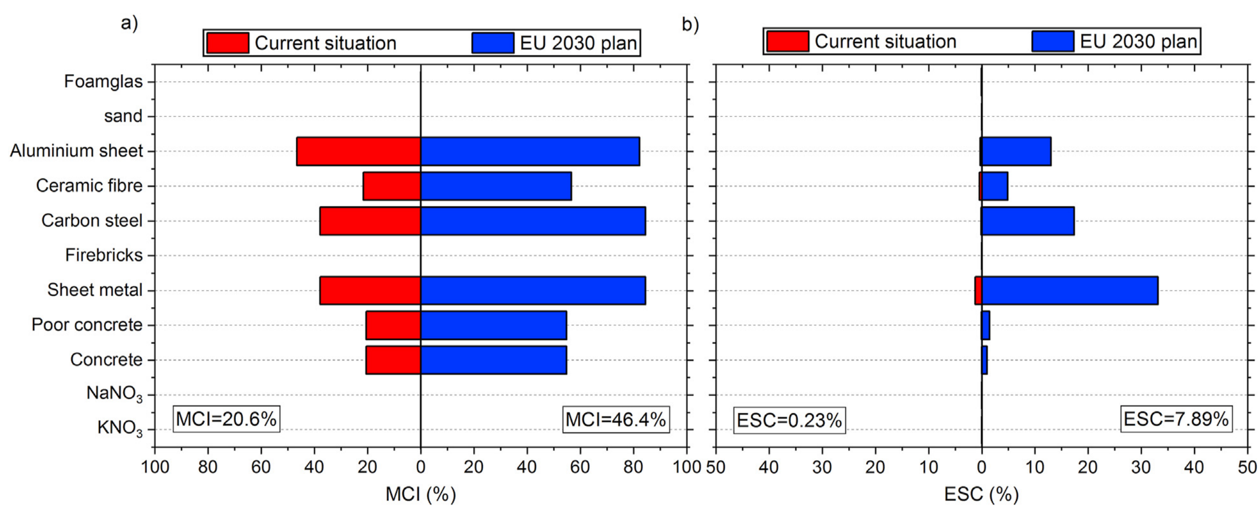

Fig. 11. The effect of increasing recycle/reuse rates by 70% & 30% on SDCS indicators where (a) *MCI* indicator and (b) *ESC* indicator.

CRediT authorship contribution statement

Mohamed Hany Abokersh: Conceptualization, Methodology, Formal analysis, Software, Data curation, Visualization, Writing – original draft. **Masoud Norouzi:** Formal analysis, Writing – original draft. **Dieter Boer:** Conceptualization, Resources, Supervision, Writing – review & editing. **Luisa F. Cabeza:** Funding acquisition, Writing – review & editing. **Gemma Casa:** Data curation. **Cristina Prieto:** Data curation, Writing – review & editing. **Laureano Jiménez:** Funding acquisition, Writing – review & editing. **Manel Vallès:** Conceptualization, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to acknowledge financial support from the Spanish Ministry of Economy and Competitiveness RTI2018-093849-B-C31 and RTI2018-093849-B-C33 (MCIU/AEI/FEDER, UE), and thank the Catalan Government (2019 FI-B-00762). The authors would like to thank the Catalan Government for the quality accreditation given to their research group (GREiA - 2017 SGR 1537, AGACAPE - 2017 SGR 1409 and 2019 FI-B-00762). GREiA is a certified agent TECNIO in the category of technology developers from the Government of Catalonia. This work is partially supported by ICREA under the ICREA Academia programme. This work is partially funded by the Ministerio de Ciencia, Innovación y Universidades – Agencia Estatal de Investigación (AEI) (RED2018-102431-T). This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 713679 and from the Universitat Rovira i Virgili (URV).

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