COOPERANT

Deliverable 5.1

Preliminary Circularity & Sustainable by design report

WP5 - Holistic Sustainability Assessment

Version 1.0

COOPERANT Key Facts

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COOPERANT Consortium Partners

N.	Partner	Acronym	Country
1	IDENER RESEARCH & DEVELOPMENT AGRUPACION DE INTERES ECONOMICO	IDE	ES
2	KRAFTBLOCK GMBH	KB	GE
3	CENTRO DE INVESTIGACIONES ENERGETICAS MEDIOAMBIENTALES Y TECNOLOGICAS	CIEMAT	ES
4	HOLOSS - HOLISTIC AND ONTOLOGICAL SOLUTIONS FOR SUSTAINABILITY, LDA.	HOLOSS	PT
5	PHASE CHANGE MATERIAL PRODUCTS LTD	PCMP	UK
6	FACHHOCHSCHULE ZENTRALSCHWEIZ HOCHSCHULE LUZERN	HSLU	CH
7	ENGICER SA	ENGI	CH

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Executive summary

Concentrated Solar Power coupled with Thermal Energy Storage (CSP-TES) is receiving increasingly attention, due to its potential to contribute to climate neutrality and industrial decarbonisation, enhancing the EU's leading role in energy-related innovations. In fact, this technology has the ability to enable electricity generation even during periods of low solar irradiation, due to the thermal storage capacity of the TES system. However, it can also present some concerns, when considering resource extraction, manufacturing, operation and end-of-life. In this regard, understanding the lifecycle impacts is essential for selecting the options with highest results and lowest environmental burdens.

The Safe and Sustainable by Design (SSbD) framework, combined with Circular Economy (CE) strategies, aim to address the major concerns related to the safety, sustainability and circularity of innovations, by minimising overall negative impacts from early design-phase. While the safety steps of the SSbD framework are focused on hazard and exposure assessment, the sustainability is closely aligned with two other major concepts: ecodesign and circularity. In fact, the SSbD approach is consistent with the ISO 14006 guidance to continuously improve sustainability performance through design, while also integrating risk minimisation and circularity as design criteria. To achieve this, eight key guiding design principles are proposed in the SSbD framework. These address material efficiency, resource use, substitution of hazardous substances, energy efficiency, emission and pollution prevention, reduction of human/environmental exposure, consideration of end-of-life and adoption of lifecycle perspective.

Considering the Design for Environmental (DfE) separate terminology for ecodesign, the remaining Design for X (DfX) strategies can be selected to address the overall environmental, health and safety issues, across a product's lifecycle or performance. In this regard, the Design for Circularity (DfC) represents a broader approach that integrates principles from various DfX methods to design products that fit into a circular economy. Furthermore, the DfC can be directly linked to the safety aspect of the SSbD framework through the safe circularity interface. This avoids the recirculation of hazardous materials and the creation of "toxic cycles", through the selection of safe and sustainable materials. These materials flows can be assessed through the Material Circularity Indicator (MCI), supporting decision-making, aligned with circular economy principles.

The SSbD framework also integrates socioeconomic dimensions, ensuring that innovations are not only beneficial to the environment but also economically viable and socially responsible. Additionally, it addresses the critical raw materials issue, through the search of solutions to minimise or replace them, due to the high risk of supply disruption that they bear.

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Based on these concepts, a methodology was developed for ongoing interaction with the developers of COOPERANT innovations. These interactions took place in months 6, 9, and 12 of the project, during the development phase of TES materials, namely Solid Stats Materials and Phase Change Materials. The purpose of this document is to present the results of this interaction, namely the ecodesign guidelines for COOPERANT CSP-TES. In this first stage, the guidelines focus on TES materials and propose perspectives for the integration of the CSP-TES system. Guidelines for the replicability of this technology in other sectors are also presented.

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List of Acronyms

CE	Circular Economy
CRM	Critical Raw Material
CSP	Concentrated Solar Power
CSP-TES	Concentrated Solar Power coupled with Thermal Energy Storage
D	Deliverable
DfC	Design for Circularity
DfE	Design for Environment
DfX	Design for X
ECHA	European Chemicals Agency
EoL	End of Life
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
GA	Grant Agreement
GHG	Greenhouse Gas
HTF	Heat Transfer Fluid
JRC	Joint Research Centre
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCSA	Life Cycle Sustainability Assessment
M	Month
MCI	Material Circularity Indicator
PCM	Phase Changing Material
PEF	Product Environmental Footprint
RES	Renewable Energy Sources
SbD	Safe by Design
SDS	Safety Data Sheet
SET Plan	Strategic Energy Technology plan
s-LCA	Social-Life Cycle Assessment
SSbD	Safe and Sustainable by Design
SSM	Solid State Material
T	Task
TES	Thermal Energy Storage
WP	Work Package

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1 Introduction

In light of the current global situation, the need to transform Europe's energy system towards independence and responsibility has come to acquire increasing importance. The European Union (EU) REPowerEU plan aims to boost Renewable Energy Sources (RES) deployment, improving energy conservation and diversifying energy supplies [1]. Concentrated Solar Power (CSP) combined with Thermal Energy Storage (TES) (CSP-TES) has gained particular interest due to is ability to enable electricity generation even during periods of low solar irradiation, supporting grid flexibility and energy security [2]. In addition, this technology is considered a key contributor to climate neutrality and industrial decarbonisation, while offering strong potential for RES integration in other sectors besides power generation [3, 4]. However, in order to truly support the transformation of the energy system, gaps in the comprehensive assessment of the environmental impacts of these technologies must be addressed. [5]

Lifecycles studies show that, despite significantly reducing the environmental impacts of the power generation sector, the raw material extraction, manufacture, operation and end-of-life of CSP-TES system can still represent points of concern, if not properly addressed. [5, 6] In fact, depending on the type of storage media, the heat transfer fluid used and the materials, different categories of environmental impacts can be affected in distinct ways. [6] In this regard, understanding the lifecycle impacts is essential for assessing which technologies have the most positive outcome and reduce overall environmental burdens, from the outset, without compromising other aspects. [5]

The Joint Research Centre (JRC) Safe and Sustainable by Design (SSbD) framework aims to address these major considerations by minimising risks, resource use and negative impacts from the early design stages [7]. In parallel, Circular Economy (CE) also highlights the positive results of adopting reuse and recyclability strategies, as well as the extension of the useful life of energy infrastructures, enhancing sustainability and competitiveness [8]. Although intrinsically connected, these two concepts are not yet systematically incorporated into CSP-TES design methodologies, with existing literature often focused on specific technical aspects, namely efficiency and performance of the systems, or specifically climate-related metrics, with little attention given to safety and socioeconomic dimensions. [9, 5]

The COOPERANT project considers the typical limitations of conventional CSP facilities, such as dispatchability, cost effectiveness and sustainability, alongside technical needs, for the uninterrupted generation of green solar power. WP5 aims to explore the application of Circularity and SSbD principles throughout developments at material and system levels. In this sense, this deliverable aims to present the guidelines developed for COOPERANT CSP-TES design, in particular for TES materials.

1.1 Purpose of the document

The purpose of Deliverable (D)5.1 is to define guidelines for the design and replicability in relevant industrial environments of the CSP-TES technologies developed in the COOPERANT project. As part of Work Package (WP)5, in particular Task (T)5.1, the efforts in this preliminary report are focused on WP2 developments, where the TES is developed.

In line with HOL's supportive role stated in the Grant Agreement (GA), this deliverable focuses on the application of the "Circularity by design" SSbD approach to TES materials, in particular Solid State Materials (SSM) and Phase Changing Materials (PCM). This guidance was provided to T2.2 and T2.3, respectively, through a preliminary analysis of the materials, for the presence of hazardous and critical raw materials (CRM), and through the SSbD premises. The definition of concepts involved, as well as the methodology applied and the guidelines obtained as a result, are presented in the document at the level of TES materials, and preliminarily at the system level, as well as for future replicability in the overall CSP-TES system.

With the growing focus on the transitioning to sustainable, accessible and eco-friendly energy, evaluating the safety and sustainability of innovations throughout the entire lifecycle, in particular, in the design phase, is vital. Therefore, and taking into account the remaining gaps in the comprehensive assessment of the impacts of TES materials, this document serves as a fundamental guide for technology developers to incorporate aspects of safety, sustainability and circularity into material decision-making, in order to ensure optimal outcomes and support Europe's energy objectives.

1.2 Objectives

The primary goal of D5.1 is to present the guidelines developed for COOPERANT CSP-TES design, considering optimisation of resource yields (circulation, recyclability and re-use of materials/chemicals) and Circularity by design approach. The scope of the deliverable covers the process of achieving those guidelines for the development of SSM and PCM, as well as the results of a preliminary analysis of the materials, for future replicability in the overall CSP-TES system, to be described in D5.6, as the Final Circularity and Sustainable by design report.

This deliverable contributes to Objective 5 (Obj#5) of COOPERANT, focused on the assessment of COOPERANT solutions viability with an integrated approach considering circularity, health, environment, social and economic impacts. Moreover, it also tackles the specific subobjectives SO5.1 and SO5.3, by proving guidelines that aim to support a significant reduction of the environmental footprint of the CSP-TES solution and improve the circularity indicators while also considering the socio-economic benefits of the project developments.

2 Relevant Background

2.1 Strengths and weaknesses of TES systems

TES systems are technologies designed to store thermal energy for later use, allowing a temporal decoupling between energy supply and demand. Most existing TES technologies for CSP rely on either **sensible heat** or **latent heat** storage mechanisms. The most mature and widely implemented approach is **sensible TES**, particularly the two-tank molten salt system, which increases the temperature of molten salts to store energy and uses the same fluid as both the storage medium and heat transfer fluid (HTF) [10]. This technology offers high thermal stability and efficient energy conversion. However, it also requires costly high-temperature-resistant materials and suffers from operational limitations, including the risk of salt freezing at low temperatures, which can lead to significant maintenance problems [11].

In contrast, **solid-state sensible TES systems**, such as those based on concrete or other high-temperature refractory materials, have been developed to provide a more cost-effective solution [12, 13]. While attractive from an economic standpoint, these systems are vulnerable to mechanical degradation, especially crack formation during repeated thermal cycling, which compromises their durability and long-term performance [14]. To mitigate these issues, recent research has focused on enhancing material resilience through approaches such as incorporating additives [15], developing fibrous composite structures [16], and utilising nanoparticle-reinforced materials to improve thermal and mechanical stability [17].

CSP-TES systems are considered a good alternative to conventional energy generation systems, assisting the achievement of climate and energy related EU objectives. In this sense, besides technical analysis, they are subjugated to environmental, socio-economic and safety assessments, presenting a set of strengths and weaknesses for each one of the dimensions.

The **strengths** of CSP-TES technology were grouped into safety, environmental, social, and economic dimensions.

Safety: TES system has the ability to use abundant, non-toxic and non-flammable materials, allowing operational safety. In fact, the choice of materials for CSP-TES systems is a critical step for supporting overall integrity, by choosing materials that improve resistance to corrosion and material degradation. Furthermore, in addition to contributing to the system's high performance, effective encapsulation can also prevent leaks and contact with the environment, acting as a protective measure for when the replacement of hazardous materials is not possible. [18, 19]

Environmental: Recent analyses of CSP-TES technology highlight the potential for reducing environmental impacts through improved storage materials. Demonstrating their potential for circular material flows, promoting the circular economy when properly designed. [20] It has significantly lower greenhouse gas emissions per kWh than fossil fuel power plants. CPS-TES can perform system service functions, reducing renewable energy waste and increasing the integration of wind and photovoltaic power without equivalent storage. It offers significant greenhouse gas (GHG) emission reductions when coupled with renewables (up to 45.4% in specific applications). [21]

Socio-economic: Analyses estimate 45-61 full-time jobs per MW installed, including direct, indirect, and induced jobs in deployment scenarios [22]. IRENA reports that a 100 MW CSP-TES plant (10 hours of storage) generates approximately 1.16 million man-days of work in engineering, procurement, and construction (46%) and operations (42%). Between 50–60% of the value of components for large-scale CSP tower plants can be sourced locally, with domestic production of key components accounting for around 10% of a plant's value. [23] The flexibility of CSP also offers positive socioeconomic impacts. The process heat supplied can be used for industrial applications, district heating, and even to drive chemical processes for solar fuels. [24] From a strictly economic perspective, CPS-TES enables the reduction of operating costs through load transfer and peak levelling. [25]

The **weaknesses** of CSP-TES technology were also grouped into safety, environmental, social, and economic dimensions.

Safety: Corrosion remains as one critical issue in high-temperature TES applications, which can result in leakage of hazardous or flammable substances, leading to spontaneous ignition and contamination [26] [27]. This way, workers are at risk of exposure not only to thermal burns, but also to chemical inhalation or skin contact. Toxicological tests have shown that prolonged exposure to degraded thermal oil can damage human and aquatic cells. [28]

Environmental: Conventional materials have critical environmental issues, such as intensive energy use in their production [29]. End-of-life routes are not well established for many materials used in TES [20]. The mirrors and thermal storage tanks occupy many square meters per MWh of generation, creating a significant footprint on land use [30]. Conventional CSP turbines typically require wet cooling, making cooling water the primary factor in water consumption. In arid regions, diverting millions of liters per year for cooling can strain local water resources [31]. Lifecycle studies highlight that even small spills of heat transfer fluid oil frequently occur during plant operations, leading to soil and aquifer contamination [28].

Socio-economic: Recent analyses confirm that the levelized cost of electricity from CSP is still higher than that from solar photovoltaic or wind power [32, 33]. High upfront investment and long construction periods can hamper competitiveness and increase dependence on subsidies. [32] An assessment of European CSP projects showed that sourcing most components from regions with lower environmental and labor standards worsens the overall sustainability profile of CSP. This indicates that global supply chains can also mitigate local benefits. This means that local job creation and income retention from a CSP project may be modest unless manufacturing and sourcing are regionalized. [33]

CSP-TES systems present a complex landscape of trade-offs, hotspots, and interdependencies across environmental, economic, social, and safety dimensions. This complexity calls for an integrated assessment framework that can systematically evaluate TES technologies across multiple sustainability criteria and identify design choices that optimize overall performance, while avoiding burden-shifting. Considering the SSbD framework, complemented by circularity principles, and Life Cycle Sustainability Assessment (LCSA), can answer to the sustainability challenges these systems present across the four dimensions. Collectively, these methodologies enable holistic assessment frameworks that help avoid burden-shifting and guide TES development towards safer, more sustainable, and economically viable outcomes.

2.2 Circularity and SSbD

The EU defines the **Circular Economy** as a model of production and consumption that involves keeping products and materials in circulation for as long as possible and minimizing waste and resource use. In the context of CE, the term **circularity** is used to refer to the measurable degree to which a product, system, or material retains its value in closed cycles. Indicators such as recyclability rate, secondary input share, and reuse potential quantify this circular performance over time. The transition from a linear to a circular economy is crucial to reducing pressure on natural resources, halting biodiversity loss, and achieving climate neutrality by 2050. Supporting the construction of a more resilient and competitive Europe. [34]

The **SSbD** concept coincides with the objectives of the CE, making the inclusion of circular principles part of its implementation [35]. The framework consists of a (re)design phase, followed by the evaluation phase, both performed along the innovation process. The (re)design phase includes the definition of principles and actions, evaluated by indicators, not only focused on safety and overall sustainability aspects, but also specific circularity requirements. Significantly, ISO 14006:2020 (Environmental management systems – Guidelines for the incorporation of ecodesign) provides formal guidance on the integration of environmental aspects into product design and development. During the redesign phase, professionals apply general ecodesign strategies derived from existing concepts such as green chemistry, green engineering, and CE principles [7]. Even though it is not an official part of the SSbD framework, ISO 14006 can offer a structured approach to implementing ecodesign.

The assessment phase is essential to ensure safety and sustainability [36]. As such, is composed of two focal points: safety assessment (hazard assessment and characterisation; exposure assessment; and risk characterisation throughout the lifecycle) and sustainability assessment (environmental sustainability assessment; and socio-economic sustainability assessment) [37]. The combination of CE and SSbD thus paves the way for cleaner and more sustainable energy technologies, supporting a greener economy in line with the objectives of Horizon Europe.

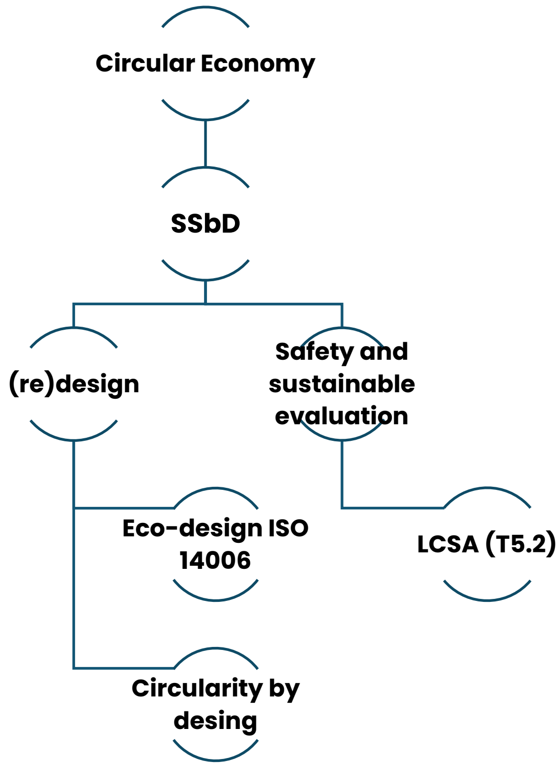

Figure 1. Connection between key concepts for this document

Figure 1 shows the conceptual relationship between the circular economy and SSbD. The following sections will describe each concept in more detail and how these relationships have been applied. The SSbD framework is expected to support renewable RES initiatives, driving innovation towards safer and more sustainable solutions, while maintaining the best efficiency possible. Adopting holistic lifecycle thinking and integrating safety and sustainability from earliest stages of the innovation leads to improvements in one or more aspects of the two dimensions, without detriment of others. This translates into responsible innovations that lead to more robust, competitive and circular industrial systems for future demands. [37]

2.2.1 Safe

The safety dimension, evaluated through the Safe by Design (SbD) approach, addresses the safety of materials/products and associated processes through the entire lifecycle, identifying risks concerning humans and the environment, from the research and development phase to end of life (EoL). [7]

According to the JRC SSbD framework, essential steps of the safety assessment include hazard and exposure assessment, enabling the classification of the safety level of substances and potential risks under specific conditions. [37] In fact, this dimension holistically comprehends hazard assessment, exposure assessment and risk characterisation. The hazard assessment is the combination of the hazard identification and hazard characterization, determining whether a chemical can cause harm based on its inherent properties, and what is the nature and severity of the adverse effects. It is also important to consider exposure assessment and risk characterisation, in order to estimate the likelihood and severity of exposure and harm for humans and the environment. To this end, the entire lifecycle should be accounted for, considering exposure scenarios, operational and use conditions and exposed population from raw materials extraction and processing, to recycling or waste management. This integrated approach prioritises hazard elimination, or where this cannot be achieved, hazard minimization, promoting sustainable innovation aligned with the objectives of the European Green Deal. [7, 37]

In the context of RES, safety plays an essential role in supporting Europe's commitment to transitioning to sustainable, clear and environmentally friendly energy. In fact, among the most common obstacles to the development of solar power plant projects in the EU, is the importance of safety and accessibility. [38] Avoiding the presence of hazardous substances from the earlier stages of development, ensures safety throughout the entire lifecycle, as well as future material cycles [39].

2.2.2 Sustainable

Complementing the safety dimension of the SSbD framework, sustainability by design focuses on identifying potential impacts throughout the lifecycle at an early stage of innovation. Sustainability has three pillars: environmental, social, and economic. In the SSbD framework, sustainability aspects are assessed through environmental lifecycle assessment and socio-economic analysis, respectively. At this stage, materials, chemicals, and processes are analysed using simplified indicators aligned with the priorities of the European Green Deal.

Life cycle assessment (LCA) is recommended for the **environmental sustainability** assessment across the lifecycle. The assessment considers relevant impact categories such as climate change, resource depletion, water use and toxicity-related indicators, following recognised methodologies such as Product Environmental Footprint (PEF) and ISO 14040/14044.

The aim of this step is not only to identify environmental hotspots but also to compare alternatives and support design optimisation. In order to ensure that the risk improvements achieved in the previous stage do not lead to a transfer of burdens throughout the lifecycle. In addition to quantifying environmental impacts, this step also supports design optimization, ensuring consistency with circular economy principles. [7] For CSP thermal storage systems, this means selecting materials and storage designs with low embedded impact, enabling the overall energy system to be more sustainable.

The **socio-economic sustainability** assessment is structured as a gradual screening process that integrates social fairness and competitiveness aspects to support early decision-making. Economic viability over the lifecycle is assessed through Life Cycle Cost (LCC) with the aim of identifying cost factors, accessibility risks, and scalability potential under realistic industrial conditions. In parallel, the social–Life Cycle Assessment (s-LCA) stage analyses potential social impacts across the supply chain, such as worker health and safety, working conditions, community effects, and governance aspects. The integrated results of LCC and s-LCA highlight critical socio-economic issues and opportunities for redesign. The aim is to ensure that innovations are not only beneficial to the environment but also economically viable and socially responsible. [7]

The SSbD framework also addresses the responsible use of resources, including CRMs, promoting material efficiency and careful management of scarce or critical inputs. The CRMs and the search for solutions to minimise or replace them are part of the SSbD principles. In addition to environmental issues, CRMs are economically important to the EU and represent a high risk of supply disruption due to dependence on countries with weaker governance. Therefore, the SSbD framework presents a value chain criticality assessment. This aims to identify vulnerabilities in the supply chain, reduce dependence on CRMs through the design of safe and sustainable chemicals and materials, and evaluate viable alternatives to mitigate economic and supply risks. The framework recommends identifying the list of materials and analysing it against the official 2023 CRM list. [7]

2.2.2.1 Ecodesign

The sustainability dimension in the SSbD framework is closely aligned with traditional ecodesign principles, extending them to the chemical and materials domain. ISO 14006:2020 "Environmental management systems – Guidelines for incorporating ecodesign" provides a framework for integrating environmental considerations into product design and development. This framework consists of six steps, namely product function specifications, environmental assessment, improvement strategies, environmental objectives, product specifications, and technical solutions. Similar to SSbD, this international standard encourages organisations to incorporate life-cycle thinking and pollution prevention into their design process.

The SSbD approach is consistent with the ISO 14006 guidance to continuously improve sustainability performance through design, but SSbD further integrates risk minimisation and circularity as design criteria. With the approach of both concepts, a holistic ecodesign methodology can be implemented. Where technologies developed considering both are intended to be not only energy efficient, but also safe, non-toxic, circular, and sustainable by design. [7, 40]

During the redesign phase, some guiding design principles are proposed in the SSbD framework, based on the principles of green chemistry and green engineering, sustainable chemistry criteria, and safety-by-design principles. The guidance highlights eight key principles of sustainability by design that designers should integrate into R&D projects. In summary, SSbD principles encourage innovators to: (1) improve material efficiency by maximising resource use and minimising waste; (2) minimise or eliminate hazardous chemicals and materials; (3) improve energy efficiency in processes and products; (4) use renewable and sustainably sourced materials or energy; (5) prevent and avoid harmful emissions and pollution; (6) reduce human and environmental exposure to any hazardous substances; (7) design for end-of-life, facilitating disassembly, recyclability, and safe disposal; and (8) adopt a full life-cycle perspective from the outset.

The terminology of product design that incorporates environmental issues has changed over the last decade, replacing the term green product design for ecological design, sustainable design, ecodesign, and Design for Environment (DfE). So, considering DfE (separate terminology for ecodesign), Design for X (DfX) can be holistically considered, such as Df Disassembly, Df EoL etc. Various guides and checklists can be used to help make sustainable design choices. Environmental, health and safety issues need to be considered at an early stage of development, and the DfX approach is a useful tool for this. [41]

The DfX strategies aim to minimise resource consumption, extend product lifetime and enable material recovery at end-of-life. It is highlighted by literature that early design decisions determine up to 80% of a product's environmental impacts. [42] This reinforces the need to embed lifecycle thinking at the design phase. The Ecodesign for Sustainable Products Regulation (ESPR) (EU) 2024/1781 establishes a horizontal framework for improving product sustainability performance across the European market [43]. The regulation introduces requirements related to durability, reusability, recycled content and information transparency. These criteria reflect the priorities defined in the Circular Economy Action Plan and are aligned with the European Green Deal objectives [43]. Whitin this, policy ecodesign becomes the technical mechanism through which circularity targets are implemented in practice, providing stakeholders with relevant guidelines to comply with new product sustainability standards.

2.2.2.2 Circularity by design

DfX techniques come in a variety of forms, from general guidelines to detailed software tools, and each addresses a different aspect of the product's lifecycle or performance.

Every DfX technique seeks to improve a particular aspect of the product being designed, such as cost or environmental impact. DfX is not a static field, new DfX methods continue to be developed in response to changing market pressures. Some examples of DfX are Df Disassembly, Df Remanufacture, Df End-of-Life, Df Reuse, Df Recycle, Df Reverse, Df Logistics, Df Sustainability, Df Environment, Df Chronic Risk Reduction, Df Energy conservation, among others. [44]

Design for Circularity (DfC) is a broader approach that integrates principles from various DfX methods to design products that fit into a circular economy. This concept is also presented in the SSbD framework through circularity from design, which is incorporated into some principles, such as principle 7 'design for end of life'. This principle is one of those that explicitly emphasizes that product designs should allow for easy disassembly and recycling. The end of life of a product should be planned at the design stage so that materials can be recovered and reused rather than ending up as waste.

The connection between circularity by design and SSbD also occurs in the **safety** scope, at the safe circularity interface, where circular loops may recirculate substances of concern. If hazardous additives enter secondary materials, recycling can create "toxic cycles" that undermine both health protection and CE credibility [45, 39]. SSbD addresses this risk by steering material selection, formulation, and processing choices towards lower hazard and higher recyclability, while limiting emissions during use and end-of-life. Designers can then prioritise solutions that are repairable and recyclable, while also avoiding substance that hider sorting, recycling yields, or safe secondary markets. Such alignment is particularly relevant for sectors with complex materials mixes, where traceability and standardisation can support both safe and circular flows.

To assess circularity, the circularity indicator presented by the Ellen MacArthur Foundation and ANSYS Granta, the Material Circularity Indicator (MCI), can be used. This metric assesses the circularity of material flows, considering factors such as the proportion of recycled content, end-of-life recyclability, and product lifespan. This methodology allows for a structured and quantitative analysis of circular performance and supports decision-making aligned with the principles of a circular economy. [46, 47]

The MCI focuses mainly on mass flows and lifetime, namely (i) the mass of virgin raw material content, (ii) the mass of waste recognized as irrecoverable after operation, and (iii) the utility factor X, which refers to the useful life by the functional value of the item. To assess the MCI of a product, it is necessary to consider the premise that its construction is a set of materials joined together in a certain way, in which each product has its own circularity and characteristics. Therefore, in order to improve the MCI of a product, it is possible to initiate actions to redesign its materials, according to the three main variables of this indicator. [20]

3 Target Scenario

The COOPERANT project aims to design and demonstrate the COOPERANT CSP-TES system. This is a pioneering technological innovation in high-performance volumetric CSP receivers, combined with hybrid TES systems that use air as a heat transfer fluid at a very high temperature. Within the scope of the deliverable, the circularity and SSbD guidelines are specifically elaborated for the materials used in the TES system, including PCM and SSM. Preliminary guidelines for system design are also proposed, as well as for replicability, defining the requirements to achieve the successful and equitable transition towards a sustainable future with clear and environmentally friendly energy, supporting more robust, competitive and circular industrial systems for future demands.

Considering the public nature of this document, sensitive information is reported in an anonymised form, to secure confidentiality.

4 Methodology Applied

In line with T5.1, the main goal of the current methodology was to define and incorporate circularity and sustainable criteria into the COOPERANT project. Focusing on WP2 developments, ecodesign guidelines were elaborated, so technology and material suppliers could consider a "Circular by Design" approach, avoid the use of CRM while ensuring the best efficiency for the product. The methodology consists of three steps, as presented in Figure 2.

The **first step** was to review the literature on updated circularity and SSbD principles and frameworks, and respective criteria applied to COOPERANT technologies. This literature review was conducted between month (M)1 and M3, and, in M4, the mapping of the processes involved in developing COOPERANT innovations was initiated, ending in M5. This activity was performed by assembling a CSP-TES system illustration, for clarification supported by the consortium on the different processes of the innovation. Finalising this step, in M6, partners were educated on the objective of the Circularity and SSbD framework, and correspondent critical aspects for an efficient implementation.

As a **second step**, the SSbD premises were presented to the SSM and PCM developers, in M5. In M6, the partners responsible for developing these materials pointed out actions for each premise, which were continuously updated, in a constant feedback cycle. This update of the actions to be considered during the selection of SSM and PCM was carried out in M9 and M12. Simultaneously, the lists of materials used for both were also collected during these interactions.

In a **third step**, by M11, a safety and CRM analysis was performed on the list of materials provided. This was intended to guide developers towards safer choices, enabling the safe circularity of these materials in the circular economy.

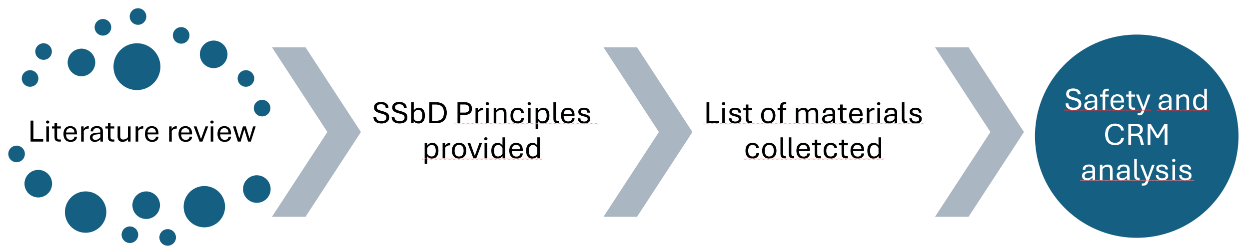

Figure 2. Visual representation of the methodology used.

These three actions laid the foundation for the development of ecodesign guidelines for the materials used in the TES system. This methodology will be expanded throughout the project to the system level. Below is a description of the second and third steps taken to establish the guidelines for COOPERANT CSP-TES.

4.1 SSbD premisses and actions

The JRC SSbD framework proposes SSbD principles, that can guide innovation by defining specific goals, the nature of the (re)design action applied and an example of the indicators to measure the success of the action towards achieving these goals. In the COOPERANT project, these principles were applied as an initial step to ensure both safety and sustainability aspects were embedded in the design stage.

The guidance highlights eight key principles of sustainability by design that designers should integrate into R&D projects, presented in Table 1.

Table 1: JRC proposed SSbD principles applied to COOPERAN project.

SSbD Principle	Examples of actions
1 - Material efficiency	Maximise yield during reaction to reduce chemical/material consumption.
	Improve recovery of unreacted chemicals/materials.
	Optimise solvent for purpose (amount, typology, and recovery rate)
	Select materials and processes that minimise the generation of waste.
	Minimise the number of chemicals used the production process.

SSbD Principle	Examples of actions
	Minimize waste generation.
	Identify occurrence of use of Critical Raw Material, towards minimizing or substituting them.
	More durable (extended life and less maintenance).
2 - Minimise the use of hazardous chemical/materials	Reduce and/or eliminate hazardous chemicals/materials in manufacturing processes.
	Eliminate hazardous chemical/materials in final products.
3 - Design for energy efficiency	Select and / or develop (production) processes considering:
	Alternative and lower energy intensive production/separation techniques
	Optimize energy efficiency of solvent recovery
	Maximise energy re-use (e.g., heat networks integration and cogeneration)
	Fewer production steps (e.g., applying lean thinking)
	Use of catalysts, including enzymes
	Reduce inefficiencies and exploit available residual energy in the process or select lower temperature reaction pathways
4 - Use renewable sources	Verify the possibility of selecting feedstocks that:
	Are renewables or secondary materials
	Do not create land competition, and / or
	Processes that use energy resources which are renewable and with low carbon emissions.
5 - Prevent and avoid hazardous emissions	Select materials that:
	Minimise the generation of hazardous waste.
	Minimise generation of emissions.
6 - Reduce exposure to hazardous substances	Eliminate or minimise risk through reduction of the use of hazardous substances.
	Analyse and avoid as much as possible the use of substances identified as SVHC.
	Consider value chain-specific regulations.
	Reduction and/or elimination of hazardous substances in manufacturing processes.
7 - Design for end-of-life	More durable.
	Easy to separate and sort.
	Valuable after their use (commercial after life).
	Truly biodegradable for uses which unavoidably lead to dispersion into the environment or wastewater.
8 - Consider the whole lifecycle	100% of waste material used in the production phase will be recycled.
	Consider the most likely use of chemical/material and if there is the possibility to recycle it.

SSbD Principle	Examples of actions
	Energy-efficient logistics.
	Reducing transport distances in the supply-chain.
	Applying responsible sourcing principles.

In this context, WP2 material developers were encouraged to guide their actions by the principles provided, to achieve safer and more sustainable innovations. Based on that, partners responsible for the SSM and PCM development outlined specific actions for each principle, to be implemented in the COOPERANT project. These actions were continuously monitored, ensuring their effective implementation and long-term compliance.

4.2 Safety and CRM analysis

During the continuous monitoring of the actions taken for each SSbD principle, the list of materials from the options studied for PCM and SSM was compiled. A preliminary analysis was carried out to identify critical and hazardous raw materials in the list provided. This was carried out based on safety data sheets (SDS), European Chemicals Agency (ECHA) registrations and the EU CRM list. This evaluation was based on the material available at the time, to provide WP2 material developers with hotspots and propose actions for their mitigation.

The preliminary **safety analysis** of materials was based on information available in ECHA registration dossiers under the REACH and CLP regulations, which offer individual compound data. In this context, the hazard characterization, based on the Globally Harmonized System (GHS) was considered. However, it is important to note that when the final products are mixtures of different compounds, properties may vary and remain insufficiently reported. [48]

Furthermore, a substance classified as containing hazardous properties in ECHA databases, may not reflect the reality of the materials used, since differences in impurities, additives, shapes and sizes, and specific formulations used by different suppliers can significantly affect the material's behaviour and risk profile. To overcome this constrains, the SDS of the materials, provided by the manufacturer or supplier, were assessed. These detail a substance's chemical properties, potential health and environmental hazards, recommended protective measures, as well as safety precautions for proper storage, handling and transportation. [49]

The **assessment of CRMs** considered both their direct and indirect presence on the CRM list 2023, considering the influence this can have on the overall environmental profile of materials incorporating this type of substances. Still within the concept of circularity, information on the three main variables of the MCI was requested from the PCM and SSM development partners. There are (1) mass of virgin raw materials used in the manufacturing phase, (2) mass of non-recoverable waste attributed to this product, and (3) utility factor variables. [20] This analysis, together with the screening of safety aspects, enabled the development of actions that align with the CE in pursuit of the creation of safe flows.

Following the initial SSbD-based screening, the preliminary results were used to connect the findings with DfX strategies (Table 2).

Table 2: SSbD principles related with Design for X.

SSbD Principle	Aspect	Design for X
1 - Material efficiency	Sustainable	Df Manufacture; Df EOL; Df Circularity
2 - Minimise the use of hazardous chemical/materials	Safety	Df Safety
3 - Design for energy efficiency	Sustainable	Df Environment
4 - Use renewable sources	Sustainable	Df Sustainability
5 - Prevent and avoid hazardous emissions	Safety	Df Safety, Df Environment; Df Sustainability
6 - Reduce exposure to hazardous substances	Safety	Df Safety
7 - Design for end-of-life	Sustainable	Df Disassembly; Df EoL; Df Circularity
8 - Consider the whole lifecycle	Sustainable	Df Waste Minimization; Df Recyclability; Df EoL

By aligning SSbD principles with DfX approaches, the methodology enabled the translation of abstract sustainability objectives into practical design actions. For instance, materials requiring special attention under SSbD safety criteria were further analysed through Design for Safety principle, while materials with recycling or recovery potential were prioritized under Design for Circularity and Design for End-of-Life. As such, ecodesign actions were developed for each DfX strategy and proposed for implementation in the COOPERANT project.

5 Results and Discussion

This section integrates the ecodesign guidelines developed specifically for the TES system and replicability in relevant industrial environments.

5.1 Literature Review

As a result of the first stage of the methodology, the concepts of circularity by design and SSbD presented in the previous section (2.2) were established. ISO 14006:2011 was identified as an ecodesign guideline that provides the steps to be followed to incorporate the concepts of circularity and SSbD into the technologies developed in the project. The six steps originally proposed can be adapted to the specifications of the product to be redesigned following ecodesign strategies. Figure 3 shows the steps for implementing ecodesign in the COOPERANT project.

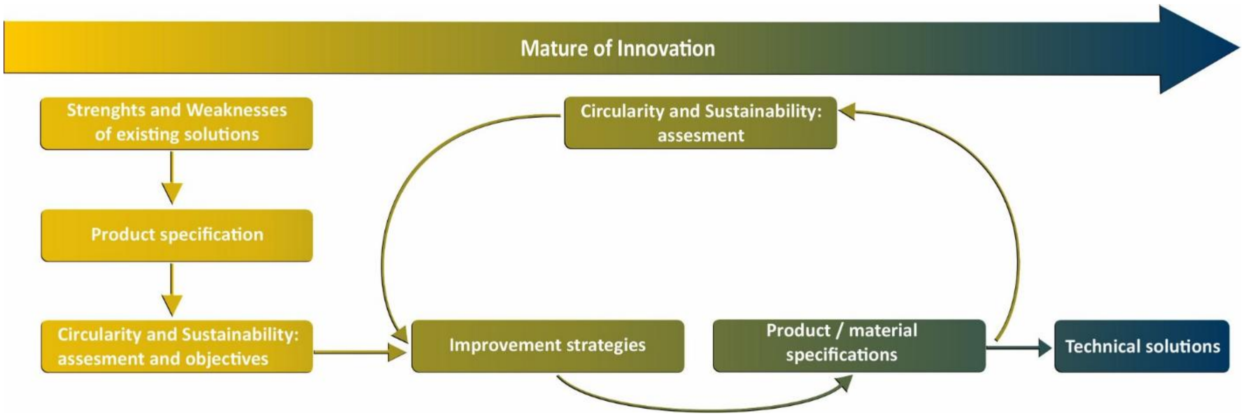

Figure 3. Ecodesign Steps for implementing ecodesign based on ISO14006 and SSbD framework.

The first step is 'strengths and weaknesses of the existing solution', presented in section 2 of this deliverable. In this first step, a review of the '**strengths and weaknesses'** of CSP-TES technology was carried out, focusing on the dimensions of safety and sustainability. This step is important for identifying the areas where actions should be focused. The next step '**product specification**', contains information about the technology to be developed. In summary, this step describes the objective of the COOPERANT project: to design and demonstrate a first-of-its-kind Concentrated Solar Power Thermal Energy Storage (CSP-TES) system. This cutting-edge technology combines a high-performance CSP volumetric receiver with hybrid Thermal Energy Storage (TES) systems, utilizing air as the heat transfer fluid (HTF) at unprecedented temperatures of up to 1000°C'.

The third step is **'Circularity and sustainable assessment and objectives'**. As this development is still in its early stages, an assessment of hotspots from a lifecycle perspective was carried out. Through this assessment, circularity and sustainability objectives were defined as key performance indicators (KPI) in D1.4.

For environmental KPIs, the LCA impact categories with the greatest influence on environmental impact identified were climate change, due to its extensive GHG emissions; land use, given the substantial spatial requirements; water use, due to its high operational demand; and human toxicity, predominantly linked to the extraction and processing of materials. The KPIs defined for these, and other impact categories of the PEF and ReCiPe methods are described in Annexe I.

Safety was considered across the defined KPIs. For example, environmental KPIs aim to reduce impacts on human and environmental health. These are measured through impact categories related to carcinogenic and non-carcinogenic toxicity, the formation of photochemical oxidants, and terrestrial, marine, and freshwater ecotoxicity in general.

Considering the MCI factors and aligned with the Strategic Energy Technology Plan (SET Plan), the Circular Economy Action Plan (2020), and the Critical Raw Materials Act, KPI were established in D1.4. for circularity perspective [50, 51, 52]. These are related to the origin of the material, useful life, and use of CRM. Safety is also transversal to circularity KPIs, specifically those aimed at reducing the use of CRM, favoring fewer toxic cycles.

The KPIs for social aspects were defined based on the s-LCA that will be carried out (T5.2) on the developed technology. All of them aim to comply with laws and align with international standards. Socio-economic KPIs were defined in accordance with the GA and involve job creation, assessment of socio-economic benefits, among others described in Annexe I.

After defining the objectives to be achieved, strategies are presented to developers in the **'improvement strategies'** stage, as presented in step two of the methodology. At this point, an interactive process begins, where strategies are presented, **'product/material specifications'** are defined, and a new evaluation is performed, enabling new improvement strategies to be formulates to address any challenges or critical aspects that may arise. This cycle allows the product development process to move forward with strategies appropriate to the maturity level of the innovation, as shown in Figure 3. During the early stages of innovation, there is more possibility for change in design and/or materials, so these cycles can be continuously applied, during the redesign phase, to support decision-making. However, as the innovation becomes more mature, the technical specifications become more defined, and the possibility for change decreases, beginning the evaluation phase, which in the case of COOPERANT is T5.2 that will perform LCSA. This interactive process is described in detail in the following section.

As a final step, there is a **'technical solution'** where the strategies actually used in the development of the material/product, with the aim of achieving the defined KPIs, are presented. Section 5.2 of this document presents the guidelines defined to date for TES materials, namely PCM and SSM. In the update version of this deliverable (D5.6), in M40, the technical solutions will be described for the entire system.

5.2 Ecodesign guidelines

Through the methodology presented, it was possible to establish preliminary ecodesign guidelines, focusing on the materials used in the developed TES. These ecodesign guidelines support the development of safe, sustainable, circular and recyclable materials, enabling the achievement of key circularity indicators for the final materials. The actions presented in Table 3 were sent to the SSM and PCM developers. The final actions taken by each were presented in D2.2 and D2.3, respectively, visible in Annexe II.

Table 3. Proposed ecodesign actions for PCM and SSM.

SSbD Principle	Design for X	Proposed ecodesign actions
1 - Material efficiency	Df Manufacture; Df EOL; Df Circularity	Redesign TES components to reduce total material mass; Prioritize modular designs for reusability; Replace CRMs with abundant alternatives when possible.
2 - Minimise the use of hazardous chemical/materials	Df Safety	Replace warning-classified materials with safer compounds; Apply intrinsic safety design in material containment (eg. encapsulation).
3 - Design for energy efficiency	Df Environment	Select low-impact synthesis routes and materials for TES media. Avoid substances with high environmental toxicity or persistence.
4 - Use renewable sources	Df Sustainability	Favor bio-based or low-impact materials for TES; analyse sustainability of supply chains for solid state materials and PCM.
5 - Prevent and avoid hazardous emissions	Df Safety; Df Environment; Df Sustainability	Prevent degradation and leakage by applying high-integrity seals; use monitoring systems to detect emissions early; prefer inherently stable materials.
6 - Reduce exposure to hazardous substances	Df Safety	Limit manual handling by designing closed-loop system; Ensure remote or automated maintenance to minimize work exposure.
7 - Design for end-of-life	Df Disassembly; Df EoL; Df Circularity	Use labelled and detachable components; Enable separation of CRM-containing materials; Plan for revalorization or reprocessing at EoL
8 - Consider the whole lifecycle	Df Sustainability	Avoid/minimize the use of CRM.

The proposed ecodesign guidelines can be divided into material-level design guidelines and general guidelines in a TES system level. This makes it possible to clarify at which stage of the design process each guideline can be addressed, considering material selection choices and design decisions, while ensuring consistent coverage of the entire product lifecycle.

Material-level design guidelines

- **Selection of safe materials:** Use abundant, non-toxic materials for all CSP–TES components, including containment. Avoid hazardous and persistent substances, choose the safest options whenever possible to improve safety and reduce human/environmental risk.
- **Avoidance or reduction of CRM:** Redesign TES components to reduce total material mass and improve material efficiency. Use abundant alternatives when possible, reducing dependency on CRMs, while maintaining functionality.
- **Preference for renewable and low-impact sourcing:** Favor bio-based or low-impact materials for TES, to reduce upstream footprint and improve supply-chain sustainability.
- **Valorisation of recycled materials and waste:** Incorporate industrial waste or by-products as thermal storage media to promote circularity. Design materials and components so that they can be recycled or safely disposed of at the end of their service life, especially when CRMs are involved.
- **Durability and longevity:** Prioritise materials that offer long service life and resist degradation to reduce the need for frequent replacements.

System-level design guidelines

- **High-efficiency thermal storage:** Design the thermal energy storage system for high efficiency and to avoid energy losses.
- **Modularity and scalability:** Adopt a modular TES design that can be scaled and replicated. Modular storage units make it easy to adjust capacity for different facility sizes and to perform maintenance or upgrades on part of the system without shutting down the entire facility. Consider reusability when developing modular designs.
- **Safety by design system**: Incorporate safety mechanisms and protections into the TES system from the design phase, avoiding hazardous emissions and decreased performance. The system should prevent failure scenarios, including degradation and leakage. Minimise operational exposure risks.
- **Maintenance and circularity:** Design the TES system to facilitate maintenance, renovation, and end-of-life handling. Use standardised components that can be replaced or upgraded and ensure easy access for inspection.

The ecodesign guidelines derived from the SSbD-aligned DfX strategies, are in line with the ESPR requirements, as practical actions to achieve policy-relevant sustainability outcomes. This way, partners are informed about the regulatory sustainability objectives that products placed on the EU market must meet, defined by the ESPR, and how to address them.

Although these requirements are set out for priority product groups (iron and steel, aluminum, textiles, furniture, tyres, mattresses, energy-related products, technology products and electronics), those that are not addressed yet, should begin preparations for regulation in the future. [53] In this sense, even though CSP-TES systems do not have specific requirements, they can be covered by the ESPR as energy technologies composed of products subject to overall requirements for circularity and sustainability.

At the material level, ESPR requirements on resource use and efficiency, presence of substances of concern and environmental impacts (carbon footprint and environmental footprint) can be achieved through the implementation of material efficiency and human/environmental impacts ecodesign guidelines. In fact, these requirements can be achieved through efficient material design choices, to reduce total material mass, replace CRMs with abundant alternatives and avoid substances with high toxicity and persistency. These are further supported by actions oriented towards sustainability and circularity, that prioritise low-impact materials for TES and favour revalorization and reprocessing of waste or by-products. Recyclability, recovery and reusability ESPR objectives are, therefore, achievable. Besides that, durability and reliability are also possible, when choosing stable material, capable of enduring long periods of time, while maintaining the required performance. [43]

Addressing material selection, leads to the achievement of these requirements when considering the system level as well, preventing degradation and leakage, and consequently emissions releasing. This way, exposure risk is also considered and reduced during operational activities, especially when coupled with strategies to limit manual handling and automatise maintenance, supporting ESPR requirements on repairability and the possibility of maintenance. This, in turn, also supports the durability and reliability of the entire system, by sustaining performance. Furthermore, modular designs that address circularity aspects, including reusability, renovation and end-of-life handling, tackle the expected generation of waste, reusability and material recovery, and even upgradability requirements. [43]

5.3 Replicability

Industries such as cement, steel, chemicals and pharmaceuticals are among the most difficult to decarbonise ('hard to abate') due to their intense and continuous heat requirements. They account for a large share of emissions. Steel and cement production together contribute more than 15% of global CO_2 emissions and rely heavily on burning fossil fuels to achieve the temperatures required for processes such as clinker calcination and iron ore reduction. Achieving the EU's climate goals, such as climate neutrality by 2050, therefore requires replacing fossil fuel-derived heat in these sectors with clean alternatives. [54, 55]

CSP–TES offers a promising solution, providing high-temperature renewable thermal energy with integrated storage for greater reliability. Many industrial processes require heat above what conventional electrification can efficiently provide, which is generally limited to ~150–200 °C (heat pump, for example), leaving a gap for processes that require medium to high temperatures. For temperatures above ~200 °C, CSP-TES systems can be ideal complements.

These systems can harness solar energy to obtain high-quality heat, while TES allows this energy to be supplied continuously, overcoming the intermittency of sunlight. This is crucial for industries that operate continuously and cannot tolerate intermittent heat supply. [55]

CSP-TES technology can reach extraordinary temperatures, as demonstrated in a recent study in which a solid granular CSP-TES dish reached outlet temperatures of up to ~1200 ºC in summer conditions. This high-temperature capability means that even processes such as steel reheating furnaces or ceramic kilns could, in principle, be powered by CSP-TES. In the cement industry, solar thermal reactors have been tested for solar-powered calcination, which is one of the most heat-intensive steps. Studies indicate that integrating a solar calciner could replace about 25 to 30% of the fossil fuel in a cement oven, reducing CO_2 emissions by about 26%. This is a substantial reduction for a single intervention, and higher solar fractions could be achieved in sunnier locations or with larger collector areas. [56]

Similarly, in steel industry, CSP can be used for processes such as scrap or air preheating, or in new routes such as solar hydrogen production for iron reduction. [57] In the chemical and pharmaceutical industries, many processes require medium temperatures, which CSP-TES can easily provide. [58, 57] In these cases, standard CSP projects can generate steam to feed existing industrial steam networks or supply hot oil to reactors, with minimal changes to plant infrastructure. Key **enablers of replicability** in these sectors include technology adaptability, modularity, and supportive policy frameworks. Thus, the guidelines for replicability of CSP-TES technology are:

- **Modularity:** contributes to adaptability. The supply of standardized modular units enables the perfect combination to meet the needs of a given plant in each sector, reducing manufacturing completion time and consequent deployment. It increases product variety without incurring additional costs. [59]

The proposed DfX strategies can be an effective approach to remove the barriers to replicability. In fact, if a system design follows the ecodesign guidelines, it's replicability in different industries and countries may be facilitated, since it responds to overall safety, sustainable and circularity concerns.

- **Material efficiency:** The reduction of the material total mass and specially prioritisation of abundant materials over CRMs, address the related geopolitical and economic risks, due to their high concentration in a few countries and the volatile nature of commodity markets. [60] This way, it reduces supply disruptions and price instability and allows replicability in different industries and countries.

- **Substitution of hazardous substances:** Adopting non-toxic, low-impact and non-persistent materials addresses the existent regulatory variability across different jurisdictions, that can lead to increased costs and operational disruptions. [61] By eliminating these challenges with the use of safer materials, replication and deployment could be facilitated.

- **High-integrity containment:** Assuring an intrinsic safety barrier through containment methods, and monitoring possible degradation and leakage, reduces emissions and secures high safety performance. These barriers are widely accepted in various industries as risk management tools, which supports a faster deployment of a given system design. [62]

- **Stability under operating conditions:** Integrating automation in systems designs for maintenance and overall operational activities is intrinsically connected with promoting safety standards for workers and infrastructures. [63] Furthermore, stable, high-performance material selection contributes directly to the safety and efficiency of the system. [64]

- **Design for disassembly and revalorization:** The optimisation of systems design for disassembly improves circularity, recyclability, and reparability, crucial for enabling a circular economy and reducing environmental footprint. This way, implementing guidelines that lead to circularity and the sustainable development of CE, is advantageous for industry and government leadership. [65]

6 Conclusion

Designing and developing safe, sustainable and circular renewable energy systems is becoming increasingly important to support the transitioning to sustainable, accessible and eco-friendly energy in the EU. These major considerations should be addressed from the early design stages, minimising risks, resource use and negative impacts, reducing the need for upstream modifications and increased costs. Therefore, this document serves as a fundamental guide for technology developers to incorporate these aspects into material decision-making. Ecodesign guidelines derived from SSbD-aligned DfX strategies enable the translation of abstract sustainability objectives into practical design actions, addressing overall sustainability and circularity criteria.

These actions can be implemented at material or system design level, which provides additional guidance on which stage of the design process each guideline can be addressed, considering the entire product lifecycle. Furthermore, by connecting the ecodesign actions with the ESPR requirements, partners are informed on how to address the regulatory sustainability objectives that products placed on the EU market must adhere to. Additionally, the proposed strategies can be an effective approach to remove the barriers to replicability. In fact, if a system design follows the ecodesign guidelines, its replicability in different industries and countries may be facilitated, since it responds to overall safety, sustainable and circularity concerns.

6.1 Next actions

Adhering to the preliminary nature of this deliverable, the methodology presented and the circularity and sustainable guidelines developed for the TES system, serve as a test case for further implementation in the overall CSP-TES system (to be further developed in WP4 during the following stages of the project).

Furthermore, as mentioned in the methodology, as the innovation evolves, technical information becomes more define, and there are fewer changes to the design, leading to the next stage of the framework, the evaluation phase. In this regard, considering the initial stage of the project, and the ongoing design phase, the guidelines now presented will be followed, later on, by the evaluation of the chosen options, through the Life Cycle Sustainability Assessment, in T5.2.

With the complete phases of (re)design and evaluation of the framework, from the combination of T5.1 and T5.2, more robust guidelines and technical solutions for the entire COOPERANT CSP-TES system will be presented in D5.6 (in M40), as the Final Circularity & Sustainable by design report.

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Annexe I

Table Annex I a. Environmental KPIs in the COOPERANT project.

KPI - indicator	Method	Reference	COOPERANT Target reduction (%)
Climate change	PEF/ReCiPE	[66] [67]	>25%
Ozone depletion	PEF/ReCiPE	[68]	>10%
Human toxicity, cancer, and non-cancer	PEF/ReCiPE	[69]	>15%
Fine-particulate matter formation	PEF/ReCiPE	[69]	5-10%
Ionizing radiation	PEF/ReCiPE	[68]	5-10%
Photochemical Oxidant Formation (Human Health & Terrestrial Ecosystems)	PEF/ReCiPE	[70]	>10%
Terrestrial acidification	PEF/ReCiPE	[69]	>20%
Terrestrial ecotoxicity	Recipe	[71]	>10%
Land use	PEF/ReCiPE	[66]	5-10%
Water use	PEF/ReCiPE	[72] [66]	>15%
Marine Ecotoxicity	ReCiPE	[73]	>10%
Freshwater Ecotoxicity	PEF/ReCiPE	[74]	>10%
Freshwater eutrophication	PEF/ReCiPE	[75]	>20%
Resource use, Minerals and metals/Mineral resource scarcity ReCiPe	PEF/ReCiPE	[51]	>10%
Fossil resource scarcity	ReCiPE	[76]	>20%

Table Annex I b - Circular KPI within the COOPERANT project.

KPI	Target COOPERANT
Increased use of material from recycled sources	>10% of weight
Improve years of operation	>25 years
Decrease use of CRM	Reduction of 10-20%

Table Annex I c. Social KPIs within the COOPERANT project

KPI - subcategory	Indicator	Unit of measurement	COOPERANT Target
	Stakeholder: Workers		[77] [78] [79]
Child Labour	Children in employment, total	% of all children, under the age of 15, in employment	
Health & Safety	Accident rate at the workplace	% of fatal and non-fatal job accidents per year	
Equal Opportunities /Discrimination	Gender wage gap	% of wage gap	**From 0 to +2***
Collective Bargaining	Trade union density	% of employees organised in trade unions	
	Stakeholder: Local Community		[80] [77]
Access to Material Resources	Certified environmental management systems (CEMs)	CEMs (ISO 14001) in the sector per 10,000 employees	**From 0 to +2***
Delocalisation and Migration	Number of international migrant workers in the sector	% of total international migrant workers in the sector	
	Stakeholder: Value Chain Actors		[79]
Promoting Social Responsibility	Membership in an initiative that promotes social responsibility	Number of companies	**From 0 to +2***

Stakeholder: Society			[77]
Corruption	Active involvement of enterprises in corruption and bribery	Number of bribery cases reported, attributable to specific activity sectors	**From 0 to +2***
Technology Development	Investments in technology development	Number of participating initiatives	
Public Commitments to Sustainability Issues	Presence of publicly available documents as promises or agreements on sustainability issues	Number of publicly available documents or agreements	
Stakeholder: Consumers			[79]
End-of-life Responsibility	Incidents of non-compliance with regulatory labelling requirements	Number of incidents of non-compliance with regulatory labelling requirements	**From 0 to +2***

The Reference Scale Approach (From -2 to 2) is used to characterise and quantify the social performance associated with each stakeholder group, as illustrated in the table below.

Table Annex I d. Reference scale for social performance evaluation. [81]

Scale level	Description
-2	No data, or Non-compliant situation; no action taken.
-1	Non-compliant situation, but actions to improve have been taken.
0	Compliance with local laws and/or aligned with international standards.
1	Progress beyond compliance is made and monitored.
2	Ideal performance; a positive output achieved and reported.

Table Annex I e. Socio-economics KPI within the COOPERANT project

KPI	COOPERANT Target
Job creation	**> 8 jobs/M€** invested in actions aligned with COOPERANT

KPI	COOPERANT Target
Local employment	**> 10 jobs/year**
Training and education	**1 Handbook**. COOPERANT-TRANSFER Handbook with training materials. (D6.2)
Equitable Job Opportunities	**2 reports** with mitigation actions to tackle all forms of discrimination. (D5.4 and D5.9)
Energy access and affordability	**1 report** with storage material results, to prove 24/7 solar thermal baseload production. (D3.1) **1 report** assessing energy cost, including <3-10 c€/kWh energy cost reduction by 2030 SET targets. (D5.8)
Industrial competitiveness	**1 report** on COOPERANT CSP-TES competitiveness, supporting the EU's economic growth goals, and enhancing global competitiveness. (D.6.3)
Social return on investment (sROI)	**1 report** accessing the socio-economic benefits of the project, including a sROI >1.

Annexe II

Table Annex II a - Ecodesign actions implemented for TES materials (both SSM and PCM).

SSbD Principle	Design for X	Ecodesign actions implemented in SSM	Ecodesign actions implemented in PCM
1 - Material efficiency	Df Manufacture; Df EoL; Df Circularity	Precise adjustment of mass/molar ratio to ensure complete reaction and maximise conversion efficiency. Optimising particle size and ensuring homogeneous mixing improves reaction kinetics and minimises side reactions. Production with minimal surplus. Waste minimised through optimisation of the subsequent production process. Selection of multifunctional raw materials and high-purity components. Minimise or eliminate additives where possible. Attention must be paid to the presence of critical substances remaining from certain processes. This is only relevant for mixers and extruders. Optimised particle size distribution in the material mixture and	Mixing of pure materials to obtain eutectic combinations. Benefit: reduction in energy consumption, reversible under controlled conditions, easy disassembly and remanufacturing, clean separation and recycling.

SSbD Principle	Design for X	Ecodesign actions implemented in SSM	Ecodesign actions implemented in PCM
		the use of lubricants to increase durability for mixers and extruders.	
2 - Minimise the use of hazardous chemical/materials	Df Safety	Care is taken not to use any hazardous chemicals/materials when selecting materials. Safety data sheets are requested, and the composition of individual raw materials is chemically analyzed if necessary.	Decreased use of hazardous materials to reduce fire risks for both transportation and operational requirements.
3 - Design for energy efficiency	Df Environment	Alternative manufacturing processes have already been investigated; the extrusion process will be used. Investigate the use of catalysts. Relevant actions for scaled-up production: Reduce inefficiencies by minimising mixing times; use binder systems that can cure at room temperature, eliminating the need for energy-intensive sintering processes; utilise available waste heat from previous process steps to preheat raw materials or accelerate curing.	Eutectic mixtures. Incorporation of thermal energy where possible.

SSbD Principle	Design for X	Ecodesign actions implemented in SSM	Ecodesign actions implemented in PCM
4 - Use renewable sources	Df Sustainability	Secondary raw materials are considered. All material development and production steps are electricity-led and can be carried out using 100% renewable energy.	Aim to utilise free solar and cool night energy for heating & cooling processes.
5 - Prevent and avoid hazardous emissions	Df safety; Df Environment; Df Sustainability	Hazardous substances are identified and excluded during the selection of suitable raw materials. No hazardous substances are generated during chemical reactions between materials.	Aim to reduce energy waste during production, utilize any residual energy, and avoid the use of hazardous materials.
6 - Reduce exposure to hazardous substances	Df Safety	Hazardous substances are identified and excluded during the selection of suitable raw materials. Certificates of analysis are requested from the supplier where available. Hazardous substances are identified and excluded during the selection of suitable raw materials. No such substances are released during the production of the material, so the final mixture does not contain any such substances.	Avoid hazardous chemicals.

SSbD Principle	Design for X	Ecodesign actions implemented in SSM	Ecodesign actions implemented in PCM
7 - Design for end-of-life	Df Disassembly; Df EoL; Df Circularity	The individual components of the storage container are joined together in such a way that they can be easily separated and sorted at the end of use. The insulation and storage medium must be recycled under certain circumstances and are not biodegradable according to current knowledge.	Aim for a service life of at least 20 years and choose materials that can be disposed of easily and in an environmentally friendly manner at the end of their service life. Minimize waste sent to landfills and use biodegradable materials as much as possible.
8 - Consider the whole lifecycle	Df Sustainability	The material residue can be recycled and reused in parts of a new mixture. Raw material transport routes are grouped and planned digitally to avoid empty runs. Local sourcing and regional transport companies reduce long-distance transport. Using low-emission transport companies can reduce CO_2 emissions and energy consumption in logistics. Selection of suppliers based on environmental, social and governance (ESG) criteria, including proof of compliance with REACH and RoHS. Preference for traceable, certified and conflict-free raw materials throughout the supply	Use of materials that are not toxic to the environment at the end of their lifecycle. Minimize waste with the goal of recycling as much as possible.

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SSbD Principle	Design for X	Ecodesign actions implemented in SSM	Ecodesign actions implemented in PCM
		chain. Use of regional or recycled materials to reduce transport effort, costs and environmental impact.	

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