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D22: Preliminary Life Cycle Assessment

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Abstract

This deliverable presents the preliminary Life Cycle Assessment (LCA) methodology and data modeling framework developed for the DIAS project, which aims to design and assess innovative geopolymer-based Thermal Energy Storage (TES) systems utilizing Construction and Demolition Waste (CDW). The report outlines the context of TES innovation within the broader goal of decarbonizing energy systems. It highlights the environmental potential of geopolymer materials as alternatives to traditional Ordinary Portland Cement (OPC)-based storage media.

The core objective of this deliverable is to define a standardized, ISO 14040/14044-compliant LCA approach for quantifying the environmental impacts of three geopolymer variants (NaOH-based, KOH-based, and a 3D printing-adapted formulation). It details the data collection strategy, system boundaries, background dataset selection (e.g., Ecoinvent, ELCD), and modeling tools (OpenLCA). In addition, the report includes insights from a comprehensive literature review to benchmark environmental performance and support impact category selection, with Global Warming Potential (GWP) and resource use as key focus areas.

This work directly supports the DIAS project's sustainability objectives by establishing the methodological basis for comparing geopolymer TES materials with conventional alternatives and

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identifying environmental hotspots for future optimization. It also sets the groundwork for full-scale LCA, contributing to the project's alignment with the EU Green Deal and circular economy goals.

1. Publishable Summary

The DIAS project introduces a novel Thermal Energy Storage (TES) approach by developing high-performance, sustainable geopolymer-based storage materials derived from Construction and Demolition Waste (CDW). Traditionally, sensible heat TES systems have relied on Ordinary Portland Cement (OPC)-based concrete due to its affordability and availability. However, OPC concrete exhibits limitations in high-temperature stability and carries a significant environmental footprint due to CO_2 emissions during its production. This innovation supports long-duration sensible heat storage applications, particularly in Concentrated Solar Power (CSP) plants, district heating systems, renewable energy enhancing grid balance, and building-level thermal management. By substituting Ordinary Portland Cement (OPC) with geopolymer binders, DIAS aims to reduce environmental impacts while improving material circularity, thermal performance, and system scalability.
This deliverable, **D22 Preliminary Life Cycle Assessment,** outlines the Life Cycle Assessment (LCA) methodology that will be employed to evaluate the environmental performance of the DIAS TES materials. It presents the definition of the goal and scope, data collection strategies, modeling tools, and impact assessment procedures aligned with ISO 14040 and ISO 14044 standards. The methodology is designed to support comparative evaluation of multiple geopolymer formulations—including NaOH-based, KOH-based, and 3D-printable variants—using OpenLCA software and Ecoinvent 3.9.1 datasets. A comprehensive literature review has informed the methodological design by benchmarking the environmental impacts of conventional and alternative TES materials. Findings consistently show that geopolymer concretes can achieve 30–64% reductions in Global Warming Potential (GWP) compared to OPC, with additional environmental benefits when sourced from recycled materials and powered by renewable energy. Studies also highlight key hotspots, such as alkali activator production and electricity-intensive processing, guiding data collection and impact modeling for DIAS.
Planned next steps include the completion of foreground data collection from experimental activities, finalization of inventory models for each material variant, execution of the impact assessment phase, and scenario-based optimization. These outcomes will support material selection, system design, and future scalability, contributing to the deployment of environmentally responsible TES solutions aligned with EU climate goals and circular economy principles.

Contents

List of Figures

List of Tables

2. Introduction

2.1 Project Background

The DIAS project introduces an innovative approach to Thermal Energy Storage (TES) systems by focusing on developing and validating sustainable, circular, and efficient materials derived from Construction and Demolition Waste (CDW). The DIAS TES system revolves around the utilization of **geopolymer concrete**, formulated using **waste red bricks,** metakaolin, and alkali activators (e.g., sodium hydroxide, potassium hydroxide, and sodium silicate). These geopolymer-based materials aim to serve as **sensible heat storage media**, offering a low-carbon alternative to conventional materials such as Ordinary Portland Cement (OPC) concrete, ceramics, or molten salts.

The DIAS TES solution is designed to meet the dual objective of providing **long-duration thermal storage capacity** while promoting **resource efficiency and circularity**. By valorizing CDW materials and integrating low-emission binders, the DIAS system contributes to the European Union's decarbonization goals, energy flexibility, and circular economy principles. The targeted applications include integrating into **district heating networks, solar thermal plants**, and **building-scale heating systems**, particularly in high solar potential regions like Cyprus.

The key innovation lies in the tailored design of the geopolymer matrix to exhibit favorable thermal properties (high heat capacity, thermal stability), structural integrity under cyclic thermal loading, and compatibility with scalable TES configurations such as packed-bed systems. By substituting high-impact primary materials with local waste-derived alternatives, DIAS aligns with **environmental sustainability** and **cost competitiveness**, making it suitable for future large-scale deployment in energy transition strategies.

2.2 Importance of Environmental Assessment in TES Material Development

As the global energy system shifts towards high shares of renewable energy, **energy storage technologies** are essential in balancing supply and demand, enhancing grid resilience, and decarbonizing end-use sectors such as heating and cooling. However, the widespread deployment of energy storage systems must be guided by technical and economic performance, and **comprehensive environmental evaluation**. This is particularly relevant in the context of **thermal energy storage**, where material choice, processing methods, and life cycle impacts can significantly influence the overall sustainability of the system.

Life Cycle Assessment (LCA) provides a scientifically rigorous and internationally recognized methodology to **quantify the environmental footprint** of TES materials across all life cycle stages—from raw material extraction to manufacturing, operation, and end-of-life. Applying LCA to TES technologies allows developers and policymakers to identify environmental hotspots, compare alternative material formulations, and guide decisions towards **low-impact, circular design choices**.

In the DIAS project, a dedicated LCA methodology will be implemented to **evaluate and optimize the environmental performance** of the geopolymer-based TES system. This assessment will serve multiple purposes: it will validate the sustainability claims of the novel materials, support the techno-economic feasibility analysis, inform future scale-up strategies, and ensure compliance with emerging regulatory and certification frameworks in Europe. By embedding LCA from the early stages of material development, the DIAS project demonstrates a commitment to evidence-based innovation. It aligns with the broader EU objectives for climate-neutral technologies.

2.3 Objective of the Report

The primary objective of this report is to present the **methodological framework** that will be adopted to perform a **comprehensive Life Cycle Assessment (LCA)** of the DIAS Thermal Energy Storage (TES) system. The focus is on establishing a robust, transparent, and scientifically credible approach to accurately quantify the environmental impacts associated with the DIAS geopolymer-based TES materials development, operation, and end-of-life management.

This methodology has been developed in alignment with internationally recognized **ISO standards**, specifically **ISO 14040** and **ISO 14044**, which define the principles, framework, requirements, and guidelines for conducting LCA studies. Adhering to these standards ensures that the DIAS LCA will be **transparent, replicable, and comparable** to other studies within the energy and materials sectors. This is crucial for enabling evidence-based decision-making, supporting funding justifications, and facilitating future commercialization and policy integration.

Moreover, the proposed LCA approach is firmly grounded in current scientific literature and best practices, as demonstrated by an extensive literature review of existing LCA studies on geopolymer materials, conventional thermal storage media, and TES systems. This review has helped to identify relevant impact categories, data sources, functional units, and modeling strategies that inform the DIAS methodology. Integrating bibliographic insights with primary and secondary data sources, such as Ecoinvent databases and experimental results, ensures that the methodology reflects academic rigor and practical applicability.

3. Methodology for LCA

The Life Cycle Assessment (LCA) methodology for the DIAS project is structured according to the internationally recognized ISO 14040 and ISO 14044 standards. These provide a rigorous and transparent framework that supports reproducibility and scientific credibility in environmental assessments. Complementing these standards, **the ILCD (International Reference Life Cycle Data System) Handbook [1]**, developed by the European Commission Joint Research Centre, offers detailed technical guidance to ensure high-quality, consistent, and comparable LCA studies across applications

By this framework, the LCA of the DIAS Thermal Energy Storage (TES) system will follow the four classical and interconnected phases of LCA:

1. Goal and Scope Definition: Establishing the purpose of the study, setting system boundaries, and defining the functional unit.
2. Life Cycle Inventory (LCI): Collecting data on material and energy flows across all stages of the product system.
3. Life Cycle Impact Assessment (LCIA): Translating inventory data into environmental impact categories using standardized impact assessment methods.
4. Interpretation: Concluding, identifying environmental hotspots, and providing improvement recommendations.

Each phase is iterative and informs the next, ensuring that decisions made during LCI, for example, can lead to revisiting and refining the scope of the study.

The Study adopts a **cradle-to-grave system boundary** to address the specific environmental implications of geopolymer-based TES materials. However, recognizing the limited data on the end-of-life management and recycling of geopolymers particularly due to their strong alkalinity and related eco- and human-toxicity concerns, the project plans to explore recycling options during later stages. If solid, reliable data cannot be found, **a cradle-to-gate** approach may be adopted instead to ensure the robustness of the assessment.

This includes raw material extraction (e.g., demolition and processing of waste bricks), processing of activators (e.g., sodium silicate, sodium hydroxide, potassium hydroxide), manufacturing and curing of the TES units, their usage in TES systems, and end-of-life treatment, including recycling or disposal.

3.1 Goal and Scope Definition

The primary goal of the DIAS LCA is to evaluate the environmental impacts of the DIAS TES material system—an innovative geopolymer concrete based on recycled bricks—throughout its life cycle. This includes assessing resource use, emissions, and waste generation, while enabling comparisons with conventional TES materials such as concrete, ceramics, or molten salts. The findings will guide optimization strategies and sustainable design choices and support dissemination to stakeholders, project partners, and regulatory authorities.

The functional unit for the analysis is defined as one cubic meter (1 m^3) of the DIAS geopolymer TES material. This unit allows for meaningful comparison with conventional alternatives and ensures scalability for industrial applications.

The system boundaries are defined as cradle-to-grave, encompassing all life cycle stages:

- Raw material extraction and preparation (e.g., recycling of bricks, production of alkaline activators),
- Manufacturing (mixing, casting, curing),
- Use phase (as a thermal storage medium),
- End-of-life (EoL) management (disassembly, reuse, recycling, or disposal).

The study is framed as an attributional LCA, following the guidelines for "micro-level decision support" defined in the ILCD Handbook. This approach models the actual environmental burdens associated with the DIAS system without accounting for larger-scale market or structural changes (as would be the case in consequential LCA). This approach supports a holistic view of the DIAS TES environmental impacts and aligns with EU sustainability goals and product environmental footprint (PEF) recommendations.

3.2 Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) phase systematically collects, quantifies, and models all relevant input and output flows associated with the DIAS Thermal Energy Storage (TES) system across its whole life cycle. This step is critical for building a robust and traceable environmental model that reflects the material and energy exchanges of the system under study.

The LCI modeling approach adopted for the DIAS project combines **foreground data** from primary experimental work carried out by project partners (Talos and FRC) with **background data** from established LCI databases. This hybrid strategy ensures high data quality, contextual relevance, and alignment with international best practices. Modeling will be performed using the **OpenLCA [2]** platform, leveraging its compatibility with the **Ecoinvent 3.9.1 [3]** database (cut-off system model) and the **European Life Cycle Database (ELCD) [4]**, which are used to represent upstream and ancillary processes not directly measured in the DIAS experimental workflow.

Foreground System

The foreground system includes all DIAS-specific operations for which primary, site-specific data are available. These encompass:

- **Material preparation**: Grinding and sieving recycled bricks using a ball mill, with measured energy consumption and throughput rates.

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- **Material mixing**: The formulation of geopolymer binders through the controlled blending of activators (e.g., NaOH, KOH, Na_2SiO_3) and aluminosilicate sources (e.g., CDW bricks, metakaolin).
- **Curing**: Oven-curing of test samples under controlled thermal conditions, with specific energy use recorded.
- **Transport logistics**: Modeled based on assumed or measured distances relevant to the Cypriot context (e.g., transporting raw materials to manufacturing sites).

Background System

The background system will be modeled using secondary datasets from **Ecoinvent** and **ELCD**, focusing on the environmental profiles of upstream processes such as:

Sodium Silicate, Sodium Hydroxide, Potassium Hydroxide, Kaolin, Metakaolin, and Waste Bricks.

Data Quality and Representativeness

By ILCD guidance and ISO standards, the following quality criteria are applied to all LCI datasets:

- **Technological representativeness**: Preference is given to data that reflects actual industrial technologies and processes used in the DIAS manufacturing chain.
- **Geographical representativeness**: Datasets representing European or Mediterranean conditions (especially Cyprus) are prioritized to improve regional relevance.
- **Temporal representativeness**: Only data from recent years (ideally post-2015) are used to reflect current energy systems and production practices.
- **Completeness and transparency**: All assumptions, approximations, and data sources are documented, with unit process modeling favored over aggregated systems to maintain traceability.

Where necessary, sensitivity analyses will be conducted to evaluate the influence of data uncertainties and modeling choices (e.g., alternative energy sources, activator compositions) on the overall environmental impact results. This comprehensive LCI approach ensures high confidence in the model outputs and lays a solid foundation for the subsequent impact assessment phase.

3.3 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) phase translates the detailed Life Cycle Inventory (LCI) data into quantifiable environmental impacts, enabling a robust evaluation of the potential consequences associated with the DIAS Thermal Energy Storage (TES) system. This assessment will be carried out in full compliance with ISO 14044 and guided by the methodological provisions of the ILCD Handbook, ensuring consistency, transparency, and scientific validity.

The **ReCiPe 2016 (H)** method will be implemented at both the **Midpoint** and **Endpoint** levels. This method is internationally recognized for its comprehensive impact coverage and compatibility with

OpenLCA and the Ecoinvent 3.9.1 database. ReCiPe allows the translation of emissions and resource data into a broad spectrum of environmental impacts, providing a well-balanced framework for technical analysis and stakeholder communication.

At the midpoint level, the following impact categories have been selected due to their relevance to TES applications and material innovation:

- **Global Warming Potential (GWP)** [kg CO_2-eq]
- **Acidification Potential (AP)** [kg SO_2-eq]
- **Eutrophication Potential (EP)** [kg N-eq]
- **Human Toxicity** [CTUh]
- **Fossil Resource Scarcity** [kg oil-eq]
- **Water Use** [m^3]
- **Particulate Matter Formation**
- **Terrestrial and Marine Ecotoxicity**

To complement this, **endpoint indicators** such as **Human Health** (expressed in DALYs), **Ecosystem Quality** (species lost/year), and **Resource Scarcity** (USD lost due to future mineral extraction) may be used to synthesize results and facilitate communication with non-technical stakeholders.

LCIA results will be presented in a **comparative format**, contrasting the DIAS geopolymer TES materials with conventional sensible heat storage (SHS) materials—specifically Ordinary Portland Cement (OPC)-based concrete, ceramics, and molten salts. This will enable clear identification of environmental "hotspots" across different life cycle stages and input materials, guiding optimization and material selection within the project.

Normalization and weighting procedures will be conducted where appropriate, following ReCiPe guidance. These techniques help rank environmental impacts and enhance interpretability, but will be applied transparently and cautiously, in line with ISO recommendations, to avoid introducing bias in interpretation or decision-making.

3.4. Key Enhancements Beyond ILCD Provisions

While the ILCD framework provides a robust foundation for LCIA, the DIAS project introduces several methodological enhancements tailored to the specificities of TES systems and regional implementation:

- **Regional Contextualization**: The assessment explicitly incorporates Cypriot electricity grid mixes, material transport routes, and local infrastructure conditions. This improves geographic representativeness—a dimension not fully developed in standard ILCD guidance.

- **Integration of Experimental Data**: Primary experimental data from DIAS partners—including energy requirements for ball milling, mixing, and curing—are used to inform the LCI model, replacing generic assumptions with measured process values.
- **Granular Modeling of Activators**: This assessment models each activator individually—sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3), and potassium hydroxide (KOH)—allowing for precise identification of environmental burdens associated with chemical formulations.

These enhancements ensure that the LCA methodology adopted by the DIAS project not only adheres to ILCD and ISO standards but also reflects state-of-the-art practices tailored for circular material systems and real-world innovation in sustainable energy storage.

3.5 Interpretation

The final phase of the LCA, interpretation, involves systematically analysing results to derive meaningful conclusions and actionable recommendations. In this phase, we will:

- Identify key contributors and hotspots (e.g., sodium silicate production, curing energy consumption).
- Evaluate the sensitivity of results to key assumptions (e.g., energy sources, transport distances, activator dosage).
- Assess the completeness, consistency, and reliability of the study.
- Explore improvement scenarios to reduce environmental impacts.

The interpretation will support material and process optimization during the DIAS project, informing the broader strategy for scaling up TES solutions in Cyprus and beyond. The transparency of assumptions and limitations will ensure that future stakeholders can adapt and expand the study based on local or updated conditions.

This methodological approach is intended to quantify environmental performance and guide sustainable innovation, contribute to circular economy goals, and ensure alignment with EU energy and climate policies such as the European Green Deal and REPowerEU**.**

4. Literature Review

4.1 Review Scope and Method

The literature review conducted for this deliverable plays a dual role. First, it provides a foundation for defining the methodological approach to the Life Cycle Assessment (LCA) of the DIAS Thermal Energy Storage (TES) system, ensuring that the project adheres to internationally recognized best practices. Second, it offers essential benchmarking information on the environmental performance of various conventional and alternative materials in sensible heat storage (SHS) applications. It allows for informed comparison against the DIAS geopolymer-based solutions.

Scope and Purpose

The review focused on studies that evaluate the life cycle environmental impacts of geopolymer concretes/Alkali-Activated Concrete (AAC)**,** and conventional SHS materials such as **Ordinary Portland Cement (OPC) concrete, ceramics, rocks, molten salts, and metals**. It also aimed to identify key parameters influencing environmental performance, such as energy consumption in manufacturing, use of industrial by-products, material transportation, and end-of-life scenarios.

4.2 Key Findings from Literature

This literature review synthesized multiple LCA studies examining the environmental performance of geopolymer concrete, AAC, and related sustainable cementitious systems. The aim was to assess methodological consistency, identify common environmental hotspots, and benchmark outcomes relevant to the DIAS project's focus on circular, geopolymer-based TES materials.

A growing body of literature underscores the environmental advantages of geopolymer-based materials over conventional OPC concrete, especially in the construction sector. In support of the DIAS project's goal to develop geopolymer TES units using CDW, this section synthesizes key findings from recent LCA studies, comparing environmental impacts, methodological rigor, and material performance. The emphasis is on Global Warming Potential (GWP), activator sensitivity, and opportunities for optimization.

The study by Amari et al. **[5]** reported a GWP of 205–240 kg CO_2-eq/m^3, achieving a 30–40% reduction compared to OPC at 354 kg CO_2-eq/m^3. These geopolymer mixes maintained excellent mechanical performance (43 MPa compressive strength) and thermal resistance up to 800°C, which aligns well with the DIAS TES application requirements. Similarly, in *Ranagiri et al. (2021)* **[6]**, alkali-activated concrete (AAC) demonstrated even lower GWP values, ranging from 131–176 kg CO_2-eq/m^3—a reduction of up to 50% versus PCC (254 kg CO_2-eq/m^3). However, both studies emphasize that sodium silicate and sodium hydroxide, commonly used activators, are major environmental hotspots, with sodium silicate alone accounting for up to 72.7% of total GWP due to its energy-intensive production.

The role of electricity sourcing was emphasized in the study conducted by *Salas et al. (2018)* ***[7]*** in Ecuador. Under a local electricity mix powered by 85% hydroelectricity, the GWP of geopolymer concrete fell to 110 kg CO_2-eq/m^3—representing a 64% improvement over OPC (302 kg CO_2-eq/m^3). These findings highlight the importance of integrating renewable energy into the production chain, a strategy DIAS can adopt by leveraging Cyprus's high solar potential.

Other studies expanded the LCA scope beyond GWP to include categories like acidification, ecotoxicity, and ozone depletion. In *"Imtiaz et al., (2021)* ***[8]***, geopolymer mixes achieved up to 57.3% lower GWP than OPC but showed elevated impacts in ecotoxicity-related categories due to the chemical nature of activators. Similarly, in *Mir, N et al. (2022)* ***[9]***, CDW-based mixes using red clay bricks recorded a GWP of 635 kg CO_2-eq/m^3—still 21% lower than OPC (807 kg CO_2-eq/m^3)—but also noted high acidification potential (5.06 kg SO_2-eq) and ozone depletion (3.14E-10 kg CFC-11-eq), mainly from grinding and electricity-intensive mixing processes.

Across all studies, LCAs were carried out according to ISO 14040 and ISO 14044 standards. Software tools like GaBi, OpenLCA, SimaPro, and Brightway2 were used alongside databases like Ecoinvent and

ELCD. Functional units were standardized to 1 m³ of material, often normalized to compressive strength to ensure fair comparison.

The study by *Dollente et al. (2021)* ***[10]*** in the Philippines reinforced the centrality of activator choice. Even with long transport distances exceeding 1400 km, total GWP increased by less than 9%, confirming that material selection is a stronger driver of environmental impact than logistics. Geopolymers formulated with rice husk ash (GP-RHA) achieved 249.8 kg CO_2-eq/m³, a 30% reduction from OPC (354.8 kg CO_2-eq/m³), with the added benefit of supporting bio-based circular economy practices.

Finally, optimization strategies were further explored in *Roux, C et al. (2024)* ***[11],*** which showed that potassium silicate dominated environmental burdens. Through partial substitution with local earth and sand, a balanced formulation (M50S50) reduced emissions while retaining acceptable mechanical performance.

In conclusion, the reviewed literature supports geopolymer concrete's environmental and technical feasibility as a lower-carbon alternative to OPC, particularly when made with recycled materials and powered by renewable energy. These studies provide valuable reference points and methodological guidance for the DIAS project. By adopting ISO-compliant LCA practices, selecting low-impact activators, and sourcing materials locally (as demonstrated in studies using CDW, rice husk ash, and renewable electricity), DIAS has the potential to deliver a geopolymer-based TES system that not only meets high-performance standards but also achieves measurable sustainability gains in alignment with EU climate goals and circular economy principles.

Table 1: *Comparative Summary of Life Cycle Assessment Studies on Geopolymer and Alkali-Activated Materials*

Study Title	**Material Type**	**GWP (kg CO_2-eq/m³)**	**Key Findings**	**LCA Methodology / Tools**
Engineering and Life Cycle Assessment of Sustainable Zeolite-Based Geopolymer ***[5]***	Zeolite + Blast Furnace Slag	205–240 (30–40% ↓ vs OPC @ 354)	High compressive strength (43 MPa); thermal resistance up to 800°C; sodium silicate = 72.7% of GWP	GaBi, ISO 14040/14044
Cradle-to-Gate LCA and Economic Assessment of AAC and BC ***[6]***	Alkali-Activated Concrete	131–176 (up to 50% ↓ vs PCC @ 254)	GWP reduction drops with higher sodium silicate/NaOH content	OpenLCA, ReCiPe 2016
LCA of Geopolymer Concrete (Ecuador) ***[7]***	Natural Zeolites + Alkali Activators	110 (64% ↓ vs OPC @ 302) with 85% hydro power	Energy source critically affects environmental performance	SimaPro, CML 2001
LCA of Precast Geopolymer Products ***[10]***	Commercial vs Rice Husk Ash Activators	241.3 (Commercial) / 249.8 (RHA); OPC: 354.8	30–32% lower GWP; long-distance transport adds <9% GWP	OpenLCA, IPCC 2013

Study Title	Material Type	GWP (kg CO_2-eq/m³)	Key Findings	LCA Methodology / Tools
LCA of Recycled Aggregate and Geopolymer Concretes ***[8]***	Fly Ash + Recycled Aggregates	Up to 57.3% ↓ GWP vs OPC	Higher ecotoxicity and ozone depletion due to activators	OpenLCA, CML 2001
LCA of CDW-Based Geopolymers for 3D Printing ***[11]***	CDW (red bricks, tiles)	635 vs OPC @ 807 (21% ↓)	High acidification (5.06 kg SO_2-eq) and ODP from electricity use	GaBi, TRACI

The reviewed literature provides a robust foundation for integrating LCA into the DIAS project's development of geopolymer-based TES systems. These studies collectively highlight the importance of using standardized LCA methodologies (e.g., ISO 14040/14044) and tools such as GaBi, OpenLCA, SimaPro, and Brightway2, ensuring that environmental impacts are measured comprehensively and consistently.

A key takeaway across the studies is the substantial reduction in GWP achieved by geopolymer concretes compared to OPC concrete. Reported GWP reductions range from 21% to 64%, depending on the material composition, energy source, and mix design. For instance, using natural zeolites and renewable electricity in Ecuador yielded a GWP of 110 kg CO_2-eq/m³, while geopolymer systems incorporating blast furnace slag and fly ash showed reductions of up to 57.3%. These examples demonstrate the environmental advantage of using waste-derived materials.

Several studies also caution that while geopolymer systems are climate-friendly, chemical activators (especially sodium silicate and potassium silicate) are significant environmental hotspots. One study quantified sodium silicate's contribution at 72.7% of total GWP, emphasizing the need for careful selection, dosage optimization, or substitution.

Moreover, studies assessing transport impacts and component-level LCA (e.g., for sodium hydroxide or rice husk ash activators) confirm that material sourcing and processing have a more substantial environmental influence than logistics. This supports the DIAS strategy of local material use and low-energy processing, which can further reduce embodied emissions.

TES Materials

The current state-of-the-art in Sensible Heat Storage (SHS) systems has been comprehensively reviewed in several key publications, offering a comparative framework highly relevant to the DIAS project's development of geopolymer-based TES systems using Construction and Demolition Waste (CDW).

The publication Khan, M. I., Asfand, F., & Al-Ghamdi, S. G. (2022) **[12]** serves as a foundational reference, emphasizing the technological maturity and practicality of SHS systems in large-scale Concentrated Solar Power (CSP) applications. It identifies a broad range of SHS materials—molten salts, concrete, ceramics, natural rocks, and granular materials (e.g., silica sand, crushed rock, alumina beads, and steel slag)—evaluated primarily on thermophysical performance, operational stability, and cost. Notably, it highlights the operational temperature limitations of traditional OPC-based concrete (degradation above 400°C), in contrast to ceramics and concrete variants designed for high-temperature stability. The DIAS geopolymer materials, engineered to withstand temperatures up to 1050°C, present a significant advancement, particularly when compared to standard OPC concretes, offering improved structural integrity under high thermal cycling.

Crucially, this study also underscores the growing importance of LCA for evaluating TES material sustainability. It sets a precedent for the DIAS project to match thermodynamic benchmarks and demonstrate superior environmental performance through systematic LCA.

Further environmental benchmarking is provided by the study *Nienborg et al. (2018)* **[13]**, part of Germany's *Speicher LCA* project. This work establishes a robust ISO 14040/14044-compliant LCA methodology, using GaBi software and tracking indicators such as GWP and Primary Energy Demand (PENRT). Water and ice had the lowest GWP and served as environmental baselines among the TES materials analyzed. By contrast, paraffin-based Phase Change Materials (PCMs) exhibited GWP values 40–130 times higher than water, while salt hydrates like SP21EK performed better with GWP values only ~12 times higher than water. Although PCM systems can outperform water in energy density at the component level, their environmental breakeven depends heavily on usage rates—salt hydrates amortize emissions after ~40 cycles, whereas paraffins require up to 260 cycles.

A broader synthesis is offered in the review by *Wickramasinghe, Y. W., & Zhang, L. (2022)* **[14]**, which compares 23 LCA studies across SHS, LHS, and THS technologies. The paper confirms that SHS systems generally have lower environmental impacts than LHS and THS. For instance, basalt-based SHS systems report GWP values as low as 1.5 g CO_2-eq/kWh, while molten salt systems range up to 30 g CO_2-eq/kWh due to nitrate production impacts. This contrast supports the DIAS project's pursuit of geopolymer alternatives, which may share basalt's mineral composition and thermal stability advantages.

Of particular interest is the Ecosocket concrete-based TES system in France, which initially produced 54,600 g CO_2-eq/kWh but achieved a 59% reduction through system optimization, showing that concrete-based systems can become environmentally viable when appropriately engineered. The DIAS system, by using CDW and avoiding clinker production, could outperform conventional OPC-based systems significantly if similar optimization and system-level design strategies are applied.

The publication Chrysostomou, C., Kylili, A., Nicolaides, D., & Fokaides, P. A. (2017) **[15]** offers region-specific benchmarks directly applicable to DIAS. This cradle-to-gate LCA quantifies the environmental impact of producing 1 tonne of ready-mix concrete in Cyprus, revealing a GWP of 824.79 kg CO_2-eq, along with an Acidification Potential (AP) of 7.67 kg SO_2-eq and an Ozone Depletion Potential (ODP) of 4.26 kg R11-eq. The high carbon intensity is primarily linked to clinker production (up to 1000 MJ/tonne) and HFO-powered concrete mixing (3113 MJ).

Table 2: *Comparative Summary of Key Studies on TES Materials and LCA Findings*

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Study Title	TES Material(s)	Key Findings	Environmental Performance / LCA	Relevance to DIAS
Progress in Research and Technological Advancements of TES for CSP **[12]**	Molten salts, OPC concrete, ceramics, rocks, granular solids (e.g., sand, alumina, steel slag)	OPC degrades above 400°C; ceramics and modified concrete perform better at high temperatures	Emphasizes the growing need for LCA in TES evaluation	DIAS geopolymers withstand up to 1050°C, surpassing OPC limitations; potential for LCA benchmarking
Life Cycle Assessment of TES Materials and Components (Speicher LCA project) **[13]**	Water, ice, paraffin PCMs, salt hydrates	Water/ice have lowest GWP; paraffins = 40–130× GWP of water; salt hydrates ~12× GWP; break-even after 40–260 cycles	ISO 14040/14044; GaBi; GWP & PENRT indicators	Though focused on PCMs, the study provides a robust LCA framework applicable to geopolymer SHS.
LCA of Sensible, Latent, and Thermochemical TES Systems for Climate Change Mitigation **[14]**	SHS: Basalt, concrete, sand; LHS: PCMs; THS: zeolites, MOFs	SHS systems have lowest GWP; basalt ~1.5 g CO_2-eq/kWh; molten salts up to 30 g CO_2-eq/kWh	Uses OpenLCA, SimaPro, CML, ReCiPe, and ILCD methods	Validates SHS as the best environmental option; basalt supports geopolymer mineral analogy
LCA of Concrete Manufacturing in Small Isolated States (Cyprus) **[15]**	Ready-mix OPC concrete	GWP = 824.79 kg CO_2-eq/tonne; AP = 7.67 kg SO_2-eq; ODP = 4.26 kg R11-eq; high emissions from clinker and HFO power	Cradle-to-gate LCA, ISO standards	Provides a Cyprus-specific baseline; DIAS can target lower emissions with CDW and no clinker.

The comparative analysis of different TES materials, including OPC concrete, highlights the evolving landscape of sensible heat storage technologies and their environmental implications. While widely used due to its availability and familiarity, OPC-based concrete exhibits significant limitations in high-temperature applications (typically degrading above 400°C). Due to its energy-intensive clinger production process, it presents a high environmental burden, particularly regarding GWP. This is particularly evident in region-specific studies, such as the Cyprus-based LCA, which reported a GWP of 824.79 kg CO_2-eq per tonne of ready-mix concrete, serving as a critical baseline for the DIAS project.

In contrast, alternative TES materials such as ceramics, basalt, and advanced geopolymer concretes show marked improvements in thermal performance and environmental impact. Basalt-based SHS systems, for example, demonstrate GWP values as low as 1.5 g CO_2-eq/kWh. At the same time, geopolymer materials—especially those incorporating recycled waste such as CDW offer a promising balance between high thermal and significant reductions in carbon footprint. Multiple studies confirm that geopolymers can reduce GWP by 30–64% compared to OPC, depending on formulation, energy sourcing, and system integration.

These findings directly influence and validate the direction of the DIAS project. By utilizing CDW as a raw material and adopting low-energy geopolymerization processes, DIAS has the potential to develop a TES solution that not only meets the demanding thermal and mechanical requirements of high-temperature energy systems but also significantly improves environmental sustainability.

Moreover, by aligning with established ISO-compliant LCA frameworks and adopting system-level optimization strategies, as seen in leading case studies, DIAS can position itself at the forefront of next-generation, circular economy-aligned TES innovations.

4.3. Literature Review Conclusion

A comprehensive review of LCA literature on materials commonly used in SHS systems highlights significant differences in environmental performance among OPC concrete, geopolymer-based alternatives, and other SHS materials such as molten salts and ceramics.

OPC concrete consistently demonstrates high GWP due to its energy-intensive clinker production process. For instance, the LCA study specific to Cyprus reported a GWP of 824.79 kg CO_2-eq/tonne of ready-mix OPC concrete, with additional impacts in acidification (7.67 kg SO_2-eq) and ozone depletion (4.26 kg R11-eq). In contrast, geopolymer concretes derived from industrial by-products (e.g., blast furnace slag, fly ash) and CDW show 30–64% lower GWP, depending on formulation and energy inputs. The lowest values were achieved when renewable electricity sources were used in manufacturing (e.g., 110 kg CO_2-eq/m^3 under 85% hydro-powered conditions in Ecuador).

Among SHS materials, basalt and ceramics demonstrated the lowest GWP values, as low as 1.5 g CO_2-eq/kWh, followed by molten salts with values up to 30 g CO_2-eq/kWh. These findings underscore the environmental superiority of solid-state materials, especially those derived from abundant or recycled feedstocks.

Best Practices in Using Ecoinvent and OpenLCA

For the LCA of the DIAS geopolymer-based TES system, best practices identified across the literature have guided the use of the OpenLCA platform, in combination with the Ecoinvent 3.x database for life cycle inventory data. OpenLCA offers flexibility in defining system boundaries, functional units, and custom process modeling, while Ecoinvent provides comprehensive, peer-reviewed datasets aligned with ISO 14040/14044 standards.

Key practices adopted include:

- Using a **cradle-to-gate boundary** for material-level assessments, planning to expand to **cradle-to-grave** for complete TES system analysis.
- Normalizing results to **1 m³ of material** or **per kWh of stored energy**, enabling comparison across studies and technologies.
- Applying impact categories such as **Global Warming Potential (GWP)**, **Primary Energy Demand (PENRT)**, **Acidification Potential**, and **Ozone Depletion Potential**, as recommended in multiple studies.

The methodological choices for the DIAS project's LCA are justified by alignment with both international standards and scientific consensus. ISO 14040/14044 compliance ensures transparency and reproducibility. The decision to use OpenLCA and Ecoinvent is supported by their widespread use in LCA studies across geopolymer and TES research, as well as their compatibility with region-specific energy mixes and waste-derived input modeling.

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As validated in previous studies, CDW as a primary raw material and avoiding clinker production align with circular economy principles and are expected to reduce GWP. Sensitivity analysis will be conducted to evaluate the environmental impact of sodium silicate and sodium hydroxide, identified as key environmental hotspots, ensuring that the final formulation balances performance and sustainability.

In conclusion, the methodological framework selected for DIAS is rooted in established best practices and directly informed by the state-of-the-art in geopolymer and TES LCA research. This positions the project to produce a credible, transparent, and comparative sustainability assessment that supports both technical decision-making and policy alignment.

5. Data Collection and Modeling Plan

5.1 Foreground Data Plan

The foreground data for the DIAS LCA involves primary data specific to the project's operational procedures and material processing. This includes precise measurements and documentation obtained directly from experimental activities carried out by project partners. Key data categories to be collected are:

- Energy Consumption: Precise measurement of energy utilized in material preparation processes (grinding and milling of CDW bricks), mixing operations of geopolymer binders, and curing processes (oven curing temperatures, durations, and related energy usage).
- Material Quantities: Detailed quantification of raw materials, including CDW-derived bricks, alkali activators (sodium silicate, sodium hydroxide, potassium hydroxide), metakaolin, water, and any additives employed during the geopolymer concrete formulation.
- Waste Generation: Quantification and characterization of waste streams generated during manufacturing and material handling processes, noting volumes, types, and management practices.
- Transport and Logistics: Data on transportation modes, distances traveled, and payload capacities, specific to the Cypriot operational context.

All collected foreground data will undergo rigorous validation through direct measurement, laboratory documentation, and operational records from the production and experimental facilities of DIAS project partners.

5.2 Background Data Plan

The background data includes upstream and ancillary processes that are not directly measured in DIAS experiments but significantly influence the environmental profile of the geopolymer-based TES materials. These processes will be modeled using established datasets from the Ecoinvent 3.9.1 database, adhering to best-practice modeling approaches and database guidance. Specific datasets to be used include:

- Sodium Silicate: Production via energy-intensive fusion processes (Ecoinvent dataset for sodium silicate production, average European conditions).
- Sodium Hydroxide (NaOH): Chlor-alkali electrolysis membrane process (Ecoinvent dataset for sodium hydroxide, 50% aqueous solution).
- Potassium Hydroxide (KOH): Electrolysis of potassium chloride brine (Ecoinvent dataset for potassium hydroxide production).
- Kaolin and Metakaolin: Ecoinvent and ELCD datasets for kaolin extraction, with additional modeling of thermal calcination processes based on recent literature (e.g., Tasiopoulou et al., 2023) **[16]**.
- Waste Bricks (CDW): Datasets covering demolition, sorting, crushing, and pre-treatment of construction and demolition waste.
- Transportation: Average freight transportation by truck within Cyprus, covering different operational distances.

Background datasets will be selected to ensure high representativeness and relevance, with preference given to datasets reflecting Mediterranean or European production conditions.

5.3 Data Validation and Quality

The quality and validity of collected data are critical for ensuring the robustness and reliability of the LCA outcomes. The DIAS project adopts rigorous validation and quality assurance protocols aligned with ISO 14040/44 and ILCD guidelines. Specifically:

- Data Assumptions: All assumptions used in modeling, including production scales, energy sources, operational efficiencies, and transport distances, will be transparently documented and subjected to sensitivity analyses to assess their influence on the overall results.
- Uncertainty Assessment: Data uncertainties, both in foreground measurements and background datasets, will be systematically evaluated. Monte Carlo simulations or sensitivity analyses will be performed in OpenLCA to quantify the impact of uncertainty on the final environmental outcomes.
- Completeness Assessment: Ensuring that the inventory is comprehensive by including all significant inputs and outputs across each life cycle stage. Periodic reviews will be conducted to identify and integrate any missing data points or overlooked processes.

5.4 Data Modeling and Analysis

The DIAS project involves three distinct geopolymer material formulations: NaOH-based geopolymer, KOH-based geopolymer, and NaOH-based geopolymer specifically formulated for 3D printing.

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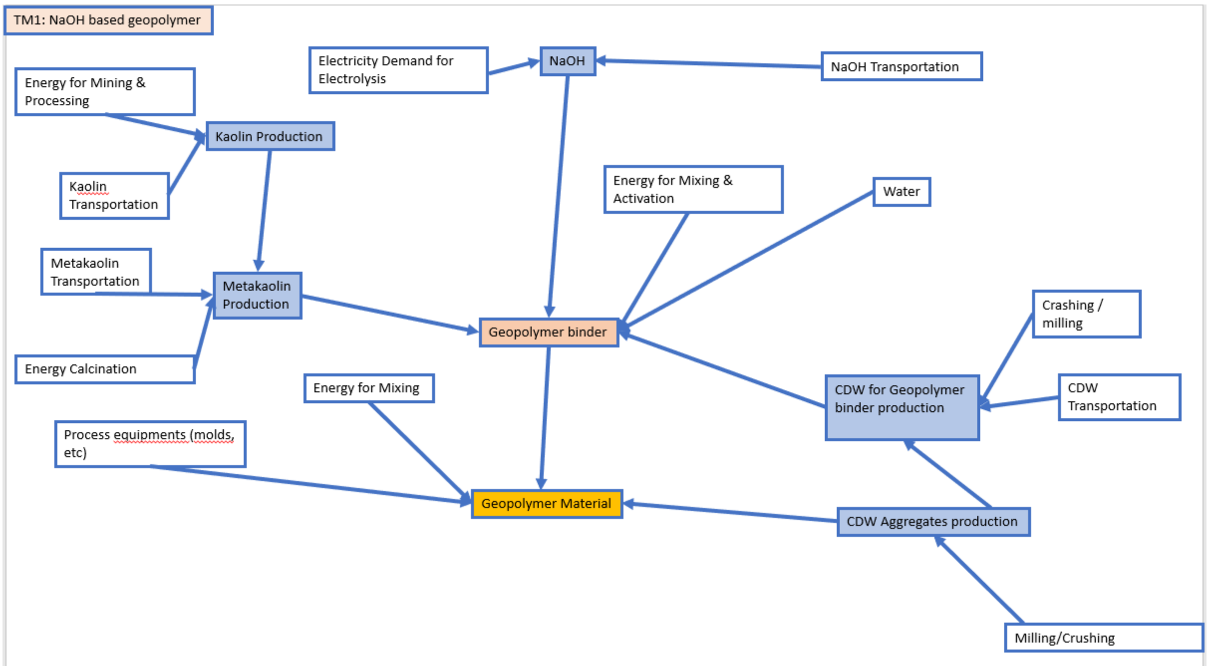

Figure 1: NaOH-Based Geopolymer for DIAS-TES casting unit

NaOH-Based Geopolymer: This model includes extensive upstream processes, such as the production and transportation of sodium hydroxide, electricity demand for electrolysis, kaolin mining, metakaolin production (including calcination energy), and transportation of raw and intermediate materials. It highlights energy use associated with mixing, activation processes, and crushing or milling of CDW.

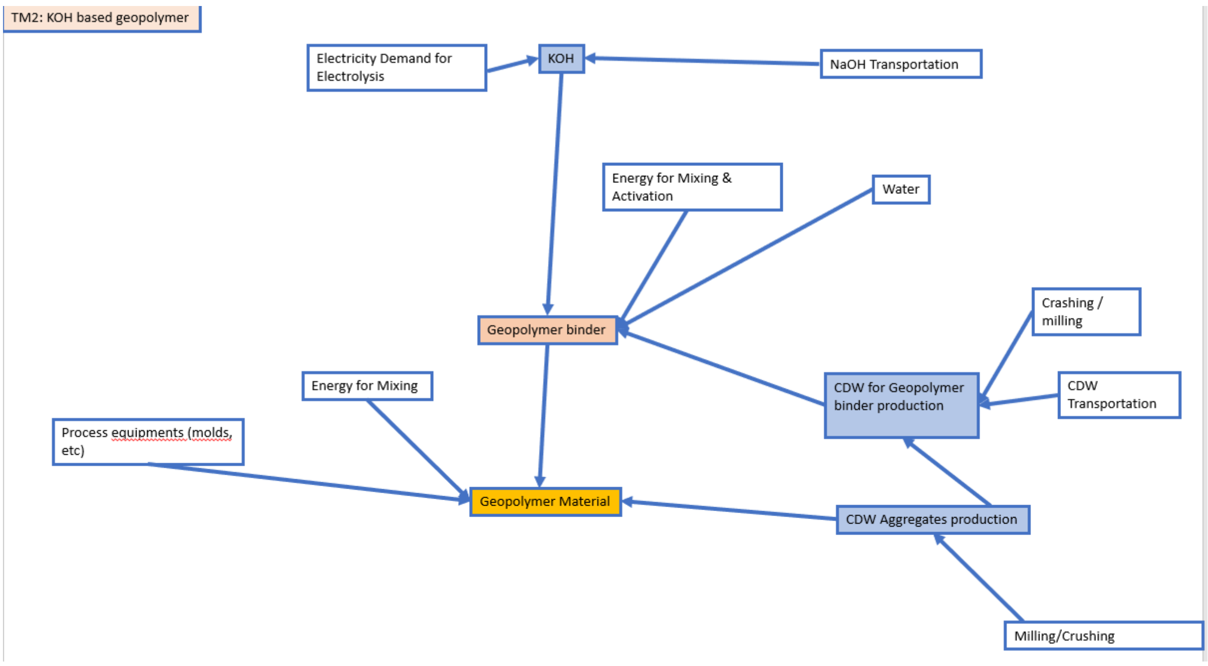

Figure 2: *KOH-Based Geopolymer for DIAS-TES casting unit*

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KOH-Based Geopolymer: Compared to the NaOH-based system, the KOH-based geopolymer simplifies upstream activities by removing kaolin and metakaolin production processes. The primary impacts are related to KOH production and its associated electrolysis energy demand, transportation, mixing and activation energy, CDW processing, and general production equipment.

The comparative analysis of these models will enable DIAS to identify key environmental hotspots for each formulation, optimizing processes to reduce environmental impacts. Both models will be thoroughly validated and calibrated using collected primary data and appropriate background data sets, ensuring accuracy, representativeness, and consistency in environmental assessments.

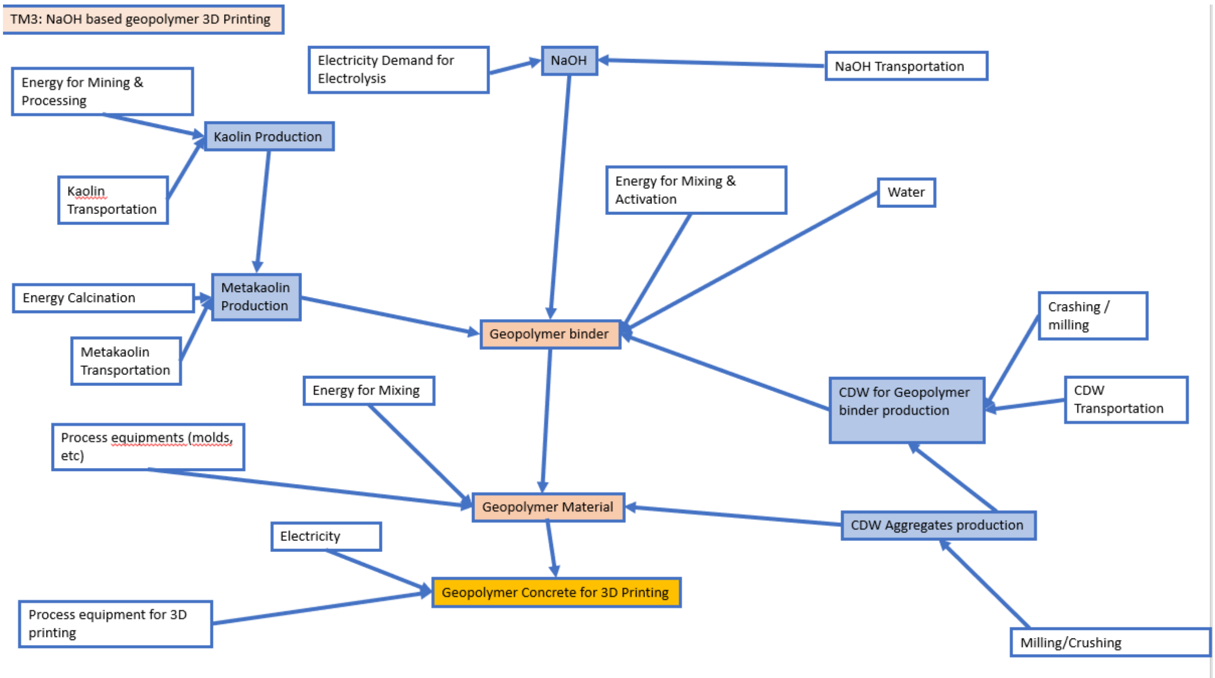

Figure 3: *NaOH-Based Geopolymer for DIAS-TES 3D-Printing unit*

NaOH-Based Geopolymer for 3D Printing: This model incorporates additional processes specific to 3D printing applications, including the manufacturing and operational energy demands of specialized 3D printing equipment. Like the standard NaOH-based geopolymer, it involves upstream activities related to kaolin and metakaolin production, energy-intensive processes for material preparation, and further incorporates energy used explicitly for printing operations.

The comparative analysis of these models will enable DIAS to identify key environmental hotspots for each formulation, optimizing processes to reduce environmental impacts. All three models will be thoroughly validated and calibrated using collected primary data and appropriate background datasets, ensuring accuracy, representativeness, and consistency in environmental assessments.

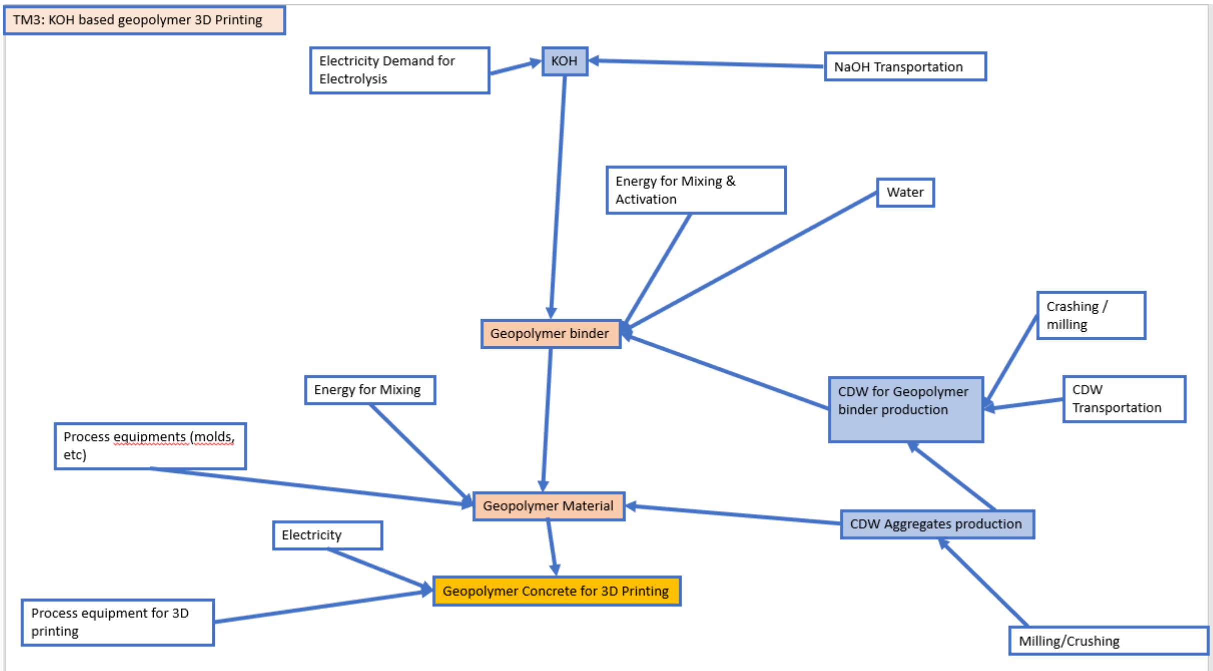

Figure 4: *KOH-Based Geopolymer for DIAS-TES 3D-Printing unit*

The KOH-based geopolymer formulation adapted for 3D printing introduces additional process stages compared to standard casting applications. Besides the upstream activities associated with potassium hydroxide (KOH) production. This model integrates energy demands related to 3D printing equipment operation (e.g., extrusion, layer-by-layer deposition) and the use of process-specific molds and supports where necessary. The overall system highlights critical stages, including crushing/milling for aggregate production, energy consumption for material mixing and activation, and additional electricity needs for operating large-scale 3D printing devices. Special attention is paid to the fabrication energy footprint since 3D printing processes are typically more energy-intensive per unit mass than traditional casting.

6. Future Work and Timeline

Future efforts in the DIAS project will focus on the implementation and validation of the LCA framework through the actual modeling of the three geopolymer formulations. This includes:

- Finalizing primary data collection during experimental trials.
- Integrating validated background datasets and refining model parameters.
- Performing full-scale LCA modeling for each TES formulation.
- Conducting scenario analyses, including energy mix sensitivity and optimization of chemical formulations.

- Completing Life Cycle Costing (LCC) and techno-economic analysis in parallel to evaluate economic feasibility.
- Drafting deliverables for interim and final reporting milestones,

The final LCA results and comparative assessments due by the end of the project year M18.

7. Conclusion

The preliminary LCA conducted within the DIAS project is a foundational step in evaluating the environmental performance of geopolymer-based TES materials derived from recycled construction and demolition waste, specifically waste bricks. The study establishes a robust framework for future environmental assessments of innovative, low-carbon material systems through a comprehensive literature review and methodological alignment with international standards (ISO 14040/44).

The analysis of state-of-the-art LCA studies on geopolymer and alkali-activated concretes reveals several key insights. First, geopolymer formulations generally outperform conventional OPC concrete in terms of GWP, with reported reductions ranging from 21% to over 60%, depending on mix design, energy source, and regional context. These environmental gains are largely attributable to replacing clinker with industrial by-products such as fly ash, slag, or zeolite. However, the studies consistently identify alkali activators, namely sodium silicate and sodium hydroxide, as the primary environmental hotspots due to their energy-intensive production processes.

The reviewed methodologies vary in terms of software tools (OpenLCA, SimaPro, GaBi), impact assessment methods (ReCiPe, CML, TRACI, ILCD), and database sources (Ecoinvent, ELCD, USLCI), but converge on cradle-to-gate system boundaries and functional units normalized per m^3 of concrete. These methodological consistencies ensure a level of comparability and highlight the importance of transparent modeling, regional adaptation, and the use of high-quality primary and secondary data.

In alignment with these findings, the DIAS LCA approach will incorporate a hybrid modeling strategy using OpenLCA and Ecoinvent 3.9.1 (cut-off system model), integrating experimental and bibliographic data. Particular emphasis will be placed on optimizing activator content, assessing regional energy sources (e.g., the Cypriot energy mix), and exploring substitution pathways for high-impact components such as sodium silicate. Furthermore, the relevance of processing energy and material transport in shaping the environmental profile has been noted, and will inform scenario analysis and sensitivity testing in the complete LCA.

In conclusion, this preliminary LCA confirms that geopolymer TES systems present a promising pathway for reducing the carbon footprint of thermal storage technologies. The insights derived from existing studies not only validate the environmental potential of DIAS materials but also offer practical guidance for data collection, impact modeling, and improvement strategies. The findings will serve as the baseline for the next phase of the project, which will involve a complete cradle-to-grave LCA including use-phase modeling, end-of-life scenarios, and circularity assessments. This will support informed decision-making and policy recommendations for sustainable materials innovation under the DIAS initiative.

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