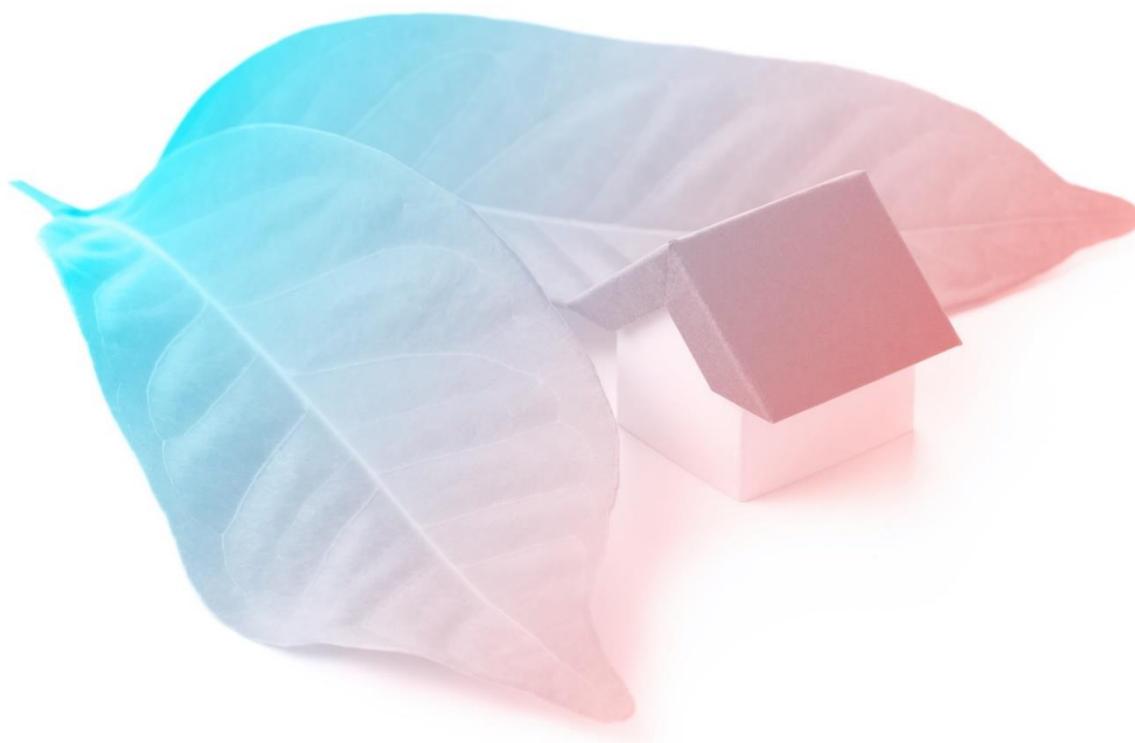# D7.3 Environmental and life-cycle assessment

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D7.3 Environmental and life-cycle assessment

Summary
This task evaluated the environmental impact of the integrated system both as a whole, and in its individual components. Additionally, it evaluated the benefits of the system compared to equivalent conventional technologies. A life cycle assessment was conducted, in accordance with current legislations and standards that direct material application, handling, disposal and recycling. Additionally, the economic benefits of the present system are evaluated. For the assessment tool, which calculates the environmental footprint of each proposed integrated storage system being defined the demo site of Thessaloniki (using input data from T3.5) followed by a corresponding life cycle costing evaluation, to feed in T7.3 Business Models development data from WP3 and 6 are used. Twenty-two environmental impact categories were estimated with mainly focus on the evaluation of a) accumulated primary energy demand, b) water consumption (scarcity), c) global warming potential (climate change), d) direct economic costs and d) the assessment of social acceptance of the renovated buildings. The inventory includes information related to a) the infrastructure materials and their transportation to the execution location, b) on-site building processes, c) operational consumption associated to the demo sites and d) the end of life of building materials. Furthermore, the environmental and economic impact evaluated regarding eight replication sites. The task will also evaluate and refine calculations made concerning durability of components, which will have as input work done in WP6, where the system is being tested in an operational environment. This work will also provide info for the cost benefit analysis of T7.3.

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	PU	Public	X

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List of Abbreviations and Acronyms

BESS	Battery Energy Storage System
CAES	Compressed air energy storage
CAPEX	Capital expenditure
CC_lt	Climate change, long term
CC_st	Climate change, short term
CCHP	Combined cooling, heating and power
CED	Cumulative energy demand
CDD	Cooling Degree Days
CO_{2eq}	Carbon dioxide equivalent
COP	Coefficient of Performance
CPC	Compound parabolic concentrator
CSP	Concentrating solar power
DC	Direct current
DHW	Domestic Hot Water
EEA	European Environment Agency
EER	Energy Efficiency Ratio
EES	electrical energy storage
EoL	End of life cost
ESS	Electrical Storage System
ETC	Evacuated tube collectors
FA	Freshwater acidification
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
FEU	Fossil and nuclear energy use
FiT	Feed-in Tariff
FPC	Flat plate solar thermal collectors
GA	Grant Agreement
GHG	Greenhouse gas emissions
GWP	Global warming potential
GWP100	Global warming potential over 100 years
HDD	Heating Degree Days
HFC	Hydrofluorocarbon
HP	Heat Pump
HTc	Human toxicity cancer
HTF	Heat-Transfer Fluid
HTnc	Human toxicity non-cancer
HVAC	Heating, Ventilation and Air Conditioning
IR	Ionizing radiations
ISO	International organization for standardization
kg	kilogram
kWh	Kilowatt-hour
LAES	Liquid air energy storage
LCA	Life Cycle Assessment
LCC	Life Cycle Cost

LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized cost of energy
LCOS	Levelized Cost of Storage
LCCOS	Life Cycle Cost of Storage
LFP	Lithium-Iron-Phosphate (battery)
LO	Land occupation, biodiversity
LT	Land transformation, biodiversity
ME	Marine eutrophication
MRU	Mineral resources use
NG	Natural Gas
NMC	Nickel-Manganese-Cobalt (battery)
NPV	Net Present Value
OD	Ozone layer depletion
OPEX	Operational expenditure.
PCM	Phase-Change Material
PENRT	Primary energy non-renewable technology
PERT	Primary energy renewable technology
PE	Primary energy demand
PM	Particulate matter formation
POF	Photochemical oxidant formation
PTC	Parabolic trough solar collectors
PV	Photovoltaic
PVC	Polyvinylchloride
PVT	Photovoltaic Thermal (hybrid solar panels)
SHTES	Sensible heat thermal energy storage
RES	Renewable energy systems
TA	Terrestrial acidification
TCM	Thermochemical Material
TES	Thermal Energy Storage
THS	Thermochemical Heat Storage
Tkm	Tonne-kilometre
TRL	Technology readiness level
TSL	Thermal System Layout
WP	Work Package

1 Introduction

Globally, around 37% of energy and greenhouse gas emissions is attributed to buildings and the construction sector (UNEP, 2022). The reduction of fossil fuels, the integration of renewable energy and of low carbon specifications in buildings, in addition to the cooling and heating energy demand reduction are among the proposed actions that can be implemented by upgrading building energy efficiency and emphasizing seasonal heat storage. Thermal energy can be stored for use at a later time when energy demand is at its highest during periods of high renewable energy production. Thermal energy storage systems (TES) are usually applied in a building for heating and hot water use. According to Aktaş and Kirçiçek, (2021) the transition to a TES system is beneficial due to the low investment and maintenance cost requirements.

Thermal storage involves energy providing to a storage medium as heat during the charging process and emitting it again during the discharging process. Latent, sensible and thermochemical heat storage (THS) are the most widely used TES systems (Cabeza et al., 2015). THS appears to have a better performance due to their high energy density, low heat loss, as well as long storage time in comparison with the other two options (Airò Farulla et al, 2020; Ali and Rosen 2011). The objective of employing TES is to conserve energy and stabilize fluctuations in power demand. In MiniStor project, thermochemical heat storage is employed in which heat is stored in an endothermic reaction (charging) whereas stored heat is released by the exothermic reaction (discharging).

By decreasing the amount of energy required to maintain comfortable indoor conditions, innovative solutions for heating, cooling, and domestic hot water in buildings can aid in the decarbonization of those structures.

Life Cycle Assessment (LCA) is a tool used in investigating the implemented procedures concerning energy storage and their impacts, throughout the entire life of a system, including the construction, operation and end of life phase. According to the European Environment Agency (EEA), LCA is the "*process of evaluating the effect that certain products or processes have on the environment over the entire period of its life thereby increasing resource-use efficiency and decreasing liabilities*". A life cycle analysis can be performed on an energy storage system and evaluate and quantify its environmental, economic or social impact. Regarding the economic impact, the Life Cycle Cost (LCC) approach is applied which evaluates the total cost related to a product or process throughout its life cycle. Like LCA, LCC is carried out during all life cycle stages; the production and construction, transportation, maintenance and end of life cost (Jacob-Lopes et al, 2021). LCC analysis involves the calculation of both internal and external costs. Internal cost incurred directly e.g. the initial cost of the investment/production, operation and maintenance cost and disposal cost. Environmental externalities are directly associated with the GHG emissions results from the LCA methodology (Mearig and Morris, 2018).

In the framework of the MiniStor project an innovative thermal and electrical energy storage system for in-situ residential installation is analyzed. MiniStor increases the use of Renewable Energy Source (RES) such as solar-based heating and minimizes the impact to the environment. MiniStor provides innovative technological solutions that are based on circular economic principles. To assess the environmental and economic impact of the MiniStor solution one location is used (the pre-demo site of Thessaloniki) and the results are utilized to provide insights on the systems used in various climatic regions. The outcomes of the LCA and LCC analysis and the conclusions regarding the environmental and economic impacts of the implementation of the innovative TES system guarantee that the objectives of MiniStor were achieved. Furthermore, the environmental impacts and the benefits of MiniStor were compared to equivalent conventional technologies. A holist approach is applied providing a valuable tool for decision-making.

1.1 Scope and Objective

The aim of this deliverable is to provide a comprehensive LCA/LCC assessment that can give insights into the environmental and economic sustainability of MiniStor. The goal is to investigate and evaluate both the environmental and the economic burden of this innovative system (as a whole, and per component) that is going to be installed in selected residential sites having different climatic conditions, thermal load needs, energy mix and costs. This novel system is going to be compared to conventional technologies that are currently used in the market to provide the necessary heating/cooling demand for residential buildings.

The scope of the document is the presentation of the LCA and LCC methodology, the definition of the LCA plan and the application of the integrated methodology to the innovative compact thermal and electrical energy storage system throughout its life cycle stages. Furthermore, the evaluation of the most significant environmental impact categories; climate change, fossil and nuclear energy use and water scarcity (as stated in the GA) took place and the various types of costs (e.g. acquisition cost, research cost, operation and maintenance cost) that have the highest economic contribution are examined. This analysis sheds light on the suggested solution's environmental and economic viability allowing the comparison with conventional TES systems for residential needs. Regarding the social perspectives on TES a variety of beliefs and viewpoints related to their acceptance, benefits, challenges, and overall impact on society are encompassed based on several studies that are described in Chapter 3.

1.2 Structure and connections with other tasks

The deliverable focuses on evaluating the environmental impact of the integrated system, as well as its components, and the advantages or drawbacks it brings when compared to conventional technologies.

A brief description of the following chapters is presented. In Charter 2, a literature review of LCA regarding energy storage technologies and the application of these systems in buildings is provided and the goal and scope of the LCA are explicitly explained. In the next step the functional unit and the system boundaries are provided. The methodology of the assessment implemented is also presented. Chapter 3 provides information on the implementation of the LCA methodology concerning MiniStor, more specifically, the life cycle inventory data set was compiled for each component of the system, the processes were developed according to MiniStor's infrastructure and operation (*e.g. operation of MiniStor based on the electricity and/or energy consumption for heating and cooling in Thessaloniki demo site and the replication sites*) and the environmental impact assessment was provided. Additionally, a comparison of three different scenarios using separate methods of heating in case of before and after MiniStor installation and operation was evaluated. Lastly, the social perspectives of thermal storage systems are provided. Chapter 4 presents the implementation of the LCC methodology. Chapter 5 introduces the baseline approach related to the economic perspective of MiniStor configuration to each site. Chapter 6 presents the life cycle cost of MiniStor and encompasses the data regarding the cost of each component to provide the overall cost that the MiniStor system will incur over its lifetime. In Chapter 7 the economic performance in different configurations and usage scenarios were calculated. Chapter 8 provides an evaluation of the cost, and the outcomes are compared with data available in the literature. Chapter 9 includes a sensitivity analysis on economic perspective with conventional system comparison in both baseline and MiniStor approach. Chapter 10 presents the conclusions.

Task 7.2 is closely integrated with various other tasks within the MiniStor project, ensuring a comprehensive evaluation of the system's performance and sustainability. Specifically, the input data generated from Task 3.5 "*Engineering, Installation Strategies, and Prototyping for Electrical Storage System*" which involves the development and implementation of strategies for the electrical storage system, feeds directly into the environmental evaluation in Task 7.2 for LCA. This data is crucial for

accurately assessing the environmental impacts of the electrical storage components. The Life Cycle Cost results obtained from Task 7.2 are going to be used in Task 7.3 "*Identification and Management of Exploitable Results*". These evaluated LCC results are utilized to update the development of the business model and conduct a thorough cost-benefit analysis. This ensures that the economic viability of the exploitable results is clearly understood and optimized. The data collected from the tasks of WP6 "*Demonstration and Evaluation*", where the MiniStor system is tested in a real operational environment, is critical for Task 7.2. This operational data allows for the evaluation and refinement of durability calculations of the system components, thereby enhancing the accuracy of both the environmental impact and economic cost assessments conducted in Task 7.2.

2 Life Cycle Assessment Framework of MiniStor

2.1 Literature review of LCA of energy storage technologies

LCA has been implemented by many researchers as a tool to quantify the environmental impact of renewable energy systems, including solar energy conversion technologies. There are studies and reviews that referred to solar collectors and their broader applications in heating and/or cooling systems (Buonomano et al., 2018; Alobaid et al., 2017; Kamel et al., 2015). Buonomano et al., 2018 investigates the replacement of conventional solar thermal collectors by hybrid Photovoltaic Thermal (PVT) / solar thermal Flat Plate Collectors (FPC), systems producing electricity, heating and cooling using a simulation model and provided a great number of comprehensive guidelines for these kinds of systems. Alobaid et al., 2017 reviewed photovoltaic thermal cooling systems investigating the collector type including hybrid PVT, FPC, evacuated tube collectors (ETC), compound parabolic concentrator (CPC) and parabolic trough solar collectors (PTC) and they assessed the efficiencies and the performance of those systems. Kamel et al., 2015 reviewed photovoltaic-thermal systems integrated with heat pumps. Most studies revealed that liquid-based solar assisted heat pumps use thermal storage to provide heating.

Innovative thermal energy storage systems may employ phase change material (PCM) or thermochemical demanding unique integration methods within the heating or cooling system. Considering PCM materials, Struhala and Ostrý; 2022 reviewed their LCA when employed in heating or cooling systems in buildings. They highlighted a lack of precise data on the environmental impacts of PCMs, as most studies rely on generic datasets, compromising accuracy. However, the use of PCMs with high energy storage density can be beneficial in heating or cooling systems, with environmental and economic payback period probably under two years. In contrast, incorporating PCMs into building is not so favorable due to the elevated embodied environmental impacts, especially for PCMs such as paraffin. Therefore, in MiniStor system salt hydrates were implemented as PCM material.

Horn et al. (2018) assessed the global warming potential (GWP) and the total primary energy of three PCM materials; paraffin (RT21) and salt hydrates (SP58 and SP21EK) as well as six TCM sorption materials. The study used data without specifying sources or characterization models. The functional unit was "*1 kWh of energy storage capacity, with the declared unit being 1 kg of material*". Salt hydrate (SP21EK) demonstrated six times lower GWP than paraffin. Nienborg et al., 2018 also investigated the GWP and the total primary energy of three PCM materials (paraffin and salt hydrate: SP 58 and SP21EK). Their impacts per storage capacity were compared to water storage. Moreover, these impacts were compared not only in material level but also in three different storage configurations (aluminium based macrocapsules with PCM, capillary heat exchanger and tube finned heat exchanger immersed in PCM). Findings revealed that on a material level, water is more environmentally friendly than other PCMs (40 - 70 times lower GWP and PE than that of paraffin in case of cooling while in case of heating, water has 80 - 130 times lower impact in both GWP and PE). Salt hydrate (SP21EK) has 12 times higher GWP impact compared to water while SP58 ~80 times. In component level, the container (78%) and the insulation (23%) are the major contributors

in case of water as storage material while in the other storage configurations the PCM material is the major contributor, both in the heating and cooling systems.

Johansson and Norrman, (2019) studied the LCA of three different PCM materials, one paraffin (octadecane), one non-fossil based organic PCM (xylitol) and one salt hydrate (manganese nitrate hexahydrate) following a cradle to grave approach and assessed: the GWP over a 100-year period (GWP100), cumulative energy demand (CED), the energy payback time in addition to health and safety concerns. They discovered that octadecane had a relatively low GWP100 of 4.5 kg CO_{2eq}/kg of octadecane produced. Xylitol, on the other hand, was favored due to its lower cumulative energy consumption of around 21.5 MJ/kg of xylitol produced and a shorter energy payback period of 1.17 years. Moreover, Madeswaran et al. 2021 investigated both the emissions and the thermal properties of PCM as separate materials and as mixtures employing the Ecoinvent database v3 and a cradle to gate approach with 1 kg PCM as the functional unit. Outcomes demonstrated that PCM mixtures have better performance than single ones. According to the emissions statistics for PCMs from raw materials to factory gate (cradle-to-gate), Na_2CO_3 produced the lowest air emissions while emitting dangerous amounts of water.

A study of the environmental assessment of a 20-year lifetime PCMs storage system with different PCM materials including RT10HC (paraffin) and SP15 (salt hydrate) compared to water was carried out by Di Bari et al. 2020. They evaluated, using a cradle to grave approach, the PCM in a material level and in a system level (infrastructure of component and use phase in a building). They provided the environmental impacts of PCM materials and showed that paraffin has higher GWP (18.30 kg CO_{2eq}./kWh material storage capacity) compared to salt hydrate (12 kg CO_{2eq}./kWh material storage capacity), in agreement with Horn et al, 2018. The implementation of PCM storage in an already existing cooling system in Helsinki showed slightly higher values of GWP and PE_{total} compared to the existing system due to the PCM material (salt hydrate) production even though the new system's had lower energy consumption. On the other hand, the installation of the same cooling system in a warmer location (Athens), revealed a 55% decrease of PE_{total} and a 10% decrease in GWP compared to the existing cooling system. The environmental impacts of material production were balanced by the operation phase (lower energy consumption of the PCM system). Furthermore, the use of a PCM storage system in the centralized heating system showed a 46% decrease in GWP owing to the higher gas consumption of the existing system.

Other studies have investigated the use of TES systems in solar power plants (Lalau et al 2022; Gasa et al, 2021) or a building (Giamas et al, 2023; Hayatina et al 2023; Herrando et al, 2022; Famiglietti et al, 2021; Guillén-Lambea et al, 2021; Zsembinszki et al, 2021) and their environmental impact with LCA. Gasa et al, 2021 evaluated a concentrating solar power (CSP) tower plant with and without a TES with a cradle to grave approach investigating 17 impact categories. The presence of thermal storage contributed to the lower environmental impact in the operation phase whereas the manufacturing and end of life impact remained comparable. Solar field, TES and HTF (molten salts) had the highest impact and the CSP without storage emitted 0.031 $kgCO_{2eq}$/kWh of electricity produced while with storage emitted 0.0098 $kgCO_{2eq}$/kWh of electricity produced. Lalau et al (2022) studied a large capacity TES (950 kWh) (*thermocline tanks*) which included conventional storage material (bauxite) and a new recycled storage material provided by industrial wastes (coal fly ashes (CFA) and SD clay). The cradle to grave analysis showed that regarding the storage material the impact of GWP is 1.64 kg CO_{2eq} /kg of bauxite and 0.37 kg CO_{2eq}/ kg of CFA ceramic while the impacts of the whole storage system concerning the GWP is 0.012 kg CO_{2eq}/kWh$_{th}$ of provided heat by the CFA ceramic storage system, 0.018 kg CO_{2eq}/kWh of provided heat by the bauxite ceramic storage system and much higher in the case of the natural gas burned in an industrial furnace (0.254 kg CO_{2eq}/kWh of provided heat).

Hayatina et al, 2023 provided a review of LCA and life cycle sustainability assessment of TES systems regarding their implementation in buildings. Famiglietti et al, 2021 conducted a cradle to grave analysis in 16 impact categories using Environmental Footprint 3.0 method considering as a functional unit 1 kWh of thermal energy to compare energy systems providing heating and domestic

hot water (DHW) systems in new buildings. Four different systems providing heating, cooling and DHW combining the TES and PCM were investigated by Guillén-Lambea et al, 2021. They followed a cradle to gate approach employing two environmental assessment methods, IPCC 2013 for GWP evaluation and ReCiPe for damage evaluation on human health, ecosystem and resources. They compared a conventional system of a gas boiler and split-type air condition with three different TES-based systems encompassing reversible heat pumps, a thermal storage tank and a PV solar field. The three TES were one sensible with water as storage material and two latent TES-based systems with PCM materials (paraffin and salt hydrate; sodium acetate trihydrate). As a FU they considered the "*energy required to meet the energy demands of the residential district*". The sensible system with water had the lower impact regarding the system construction whereas the conventional one had the highest environmental impact. In addition to this, Herrando et al, 2022 conducted an extensive life cycle assessment investigating a system that is capable of cooling, heating, and producing domestic hot water and electricity. The functional unit is "*building energy system*" and assessed the environmental impact of the system in twenty-two impact categories (ReCiPe 2016 Endpoint method) and the GWP100 (IPCC method). They demonstrated that this system had the potential to minimize the environmental footprint of buildings across various solar irradiance levels and electricity mix scenarios. The system is considered valuable even in regions with limited solar exposure or in places with predominantly clean energy sources. A comparison of impacts of a conventional PV, of a grid-based system (with a reversible heat pump) with the new PVT system revealed a 30% decrease of the PVT compared to a grid-based system.

An LCA of an innovative hybrid electrical and TES for houses in Mediterranean climate was conducted by Zsembinszki et al, 2021. The innovative system included a "*sorption storage and dry cooler, latent heat thermal energy storage (PCM tank), electrical storage and DC bus, compression DC-driven reversible heat pump, solar field of Fresnel collectors, sensible heat storage (buffer tank), and PVs*". As a reference system a system with the following was assumed: a solar collector, DHW storage tank, gas boiler and a reversible heat pump. The GWP100 and the short term (GWP20) ones were estimated in addition to the twenty-two impact midpoint impact categories and endpoint damages. The functional unit considered was "*1 m² of living room*". The overall environmental impacts of the innovative system (664 kg CO_{2eq}/m²) were lower than those of the reference system 1182 kg CO_{2eq}/m². Furthermore, in the innovative system the contribution of the latent TES system was 29%, of the sorption storage 27% and of the solar field 21%.

Based on the above studies, it can be concluded that the presence of thermal storage notably decreases environmental impact during the operational phase. Furthermore, an innovative energy system that can provide heating, cooling and DHW within a building can achieve 30-40% lower environmental impacts compared to a conventional system. TES designs, such as those incorporating PCM and hybrid electrical systems, demonstrate lower GWP over their life cycle compared to conventional systems, highlighting their potential for enhancing energy efficiency in buildings. However, challenges such as lack of data, expertise, and best practices, especially regarding PCM, persist in limiting broader TES adoption. Table 1 presents all the reviewed LCA studies on PCM materials, on thermal storage systems and hybrid thermal and electrical storage systems implemented in buildings.

Table 1. Literature review of LCA studies with PCM and thermal storage systems

Reference	Title	Results	Functional unit	Boundaries	Impact categories
Bonamente and Aquino 2020	Environmental Performance of Innovative Ground-Source Heat Pumps with PCM Energy Storage	Baseline scenario of a GSHP system: 0.130 $kgCO_{2eq}$/kWht (grid) and 0.0356 $kgCO_{2eq}$/kWht (PV) PCM-TES: 0.108 $kgCO_{2eq}$/kWht (grid) and 0.0312 $kgCO_{2eq}$/kWht (PV)	1 kWh of thermal energy produced (kWht)	Cradle to grave approach	Mid-point indicators: global warming, photochemical oxidation; acidification; eutrophication End-point indicators: - human health; ecosystems; resources.
Di Bari et al. 2020	Energy efficiency can be reached by utilization of materials with thermal storage potential; among them, phase change materials seem to be promising.	PCM: Paraffin: 18.30 kg CO_{2eq}./kWh Salt hydrate: 12.02 kg CO_{2eq}./kWh Cooling system with PCM storage in an office block: 1.55 kg CO_{2eq}./m^2 net surface year Centralized Heating System with PCM Storage: 10.21 kg CO_{2eq}./m^2 net surface year	Material level: impact/kWh material storage capacity System level: $kgCO_{2eq}$./m^2 net surface year	Cradle to grave approach	GWP, PE; PERT; PENRT
Famiglietti et al, 2021	Environmental Life Cycle Assessment scenarios for a district heating network. An Italian case study	District heating: 0.208 kg CO_{2eq}./kWh$_{th}$ Heat pumps: 0.118 kg CO_{2eq}./kWh$_{th}$ Projection to future (2030) District heating: 0.081 kg CO_{2eq}./kWh$_{th}$ Heat pumps: 0.089 kg CO_{2eq}./kWh$_{th}$	1 kWh of thermal energy	Cradle to grave approach	16 impact categories of Environmental Footprint 3.0 method
Gasa et al, 2021	Life Cycle Assessment of a Concentrating Solar Power Plant in Tower Configuration with and without Thermal Energy Storage	CSP 120MW plant without TES: 0.0069 kg CO_{2eq} /kWh produced CSP 120MW plant with TES: 0.0037 kg CO_{2eq} /kWh produced	1 kWh of electricity produced	Cradle to grave approach	17 midpoints and 3 endpoints categories (human health, ecosystem quality, and resource scarcity)
Guillén-Lambea et al, 2021	Sustainable enhancement of district heating and cooling configurations by combining thermal energy storage and life cycle assessment	Four Systems and annual emissions 1) Reference/conventional system (gas boiler and split-type air conditioners) → 1,206,260 kg CO_{2eq} TES-based systems (PV Solar field, reversible heat pump, storage tank) 2) one sensible TES-based systems (water) → 166,658 kg CO_{2eq} 3) latent TES-based systems (paraffin) → 151,524 kg CO_{2eq} 4) latent TES-based systems (sodium acetate trihydrate, SP58). → 179,603 kg CO_{2eq}	"energy required to meet the energy demands of the residential district"	Cradle to gate approach	GWP100 and endpoint categories (damage on human health, ecosystem quality and resources)

Herrando et al, 2022	Life Cycle Assessment of solar energy systems for the provision of heating, cooling and electricity in buildings: A comparative analysis	Solar combined cooling, heating and power (S-CCHP) system VS grid-based system 4.48 kPts vs 8.87 kPts (endpoint) 82.4 tons CO_{2eq} vs 166.9 tons CO_{2eq} (GWP) 30% less environmental impact than grid-based system	"Building energy system"	Cradle to gate approach	GWP100 and endpoint categories (damage on human health, ecosystem quality and resources; 22 impact categories)
Horn et al, 2018	Life cycle assessment of innovative materials in thermal energy storage in buildings	PCM Paraffin: 45 kg CO_{2eq} /kWh material storage capacity Salt hydrates: SP21 EK: 38 kg CO_{2eq} /kWh material storage capacity SP58: 6 kg CO_{2eq} /kWh material storage capacity Sorption materials, TCM 0.5 kg CO_{2eq} /kg material (magnesium sulfate, salt hydrate) – 0.75 kg CO_{2eq} /kg material (CAU-10-H, metal organic framework)	1 kWh of thermal energy stored within the materials 1kg of storage material 1 kWh of thermal energy delivered to the distribution system	Cradle to grave approach	GWP and PE consumption (*non-renewable and renewable*)
Johansson & Norrman, 2019	Life cycle analysis on phase change materials for thermal energy storage.	PCM Organic: Octadecane, Xylitol Salt hydrate: Manganese Nitrate Hexahydrate Best option: GWP: 4.5 kg CO_{2eq}/kg Octadecane produced CED: Xylitol more preferable in terms of cumulative energy demand	1 kg of the selected PCM	Cradle to grave approach	GWP100, CED, energy payback time, sustainability in use and in production
Lalau et al 2022	Energy analysis and life cycle assessment of a thermal energy storage unit involving conventional or recycled storage materials and devoted to industrial waste heat valorisation	Impacts of TES materials GWP CFA ceramic: 0.37 kg CO_{2eq}/ kg CFA GWP Bauxite: 1.64 kg CO_{2eq} /kg bauxite CED CFA ceramic: 8.2 MJ_{eq} kg CFA CED Bauxite: 28.5 MJ_{eq} / kg bauxite Impacts of storage systems GWP CFA ceramic: 0.012 kg CO_{2eq}/kWh$_{th}$ of provided heat GWP bauxite ceramic: 0.018 kg CO_{2eq}/ kWh$_{th}$ of provided heat GWP natural gas burned in industrial furnace: 0.254 kg CO_{2eq}/ kWh$_{th}$ of provided heat CED: 65, 74 and 4375 MJ_{eq} / MWh$_{th}$ (Coal fly ash, Bauxite ceramic and natural gas burned in industrial furnace)	Provide 1 MW$_{th}$ at the rate of 2 GWh year^{-1} during 25 years	Cradle to grave approach	5 selected indicators: CED, GWP, abiotic depletion potential, particle matter and freshwater eutrophication.

Maheswaran et al. 2021	Life cycle inventory and performance analysis of phase change materials for thermal energy storages	Better performance of PCM mixtures Potassium nitrate (65.31%) + potassium carbonate (34.69%) used less electricity. Emissions of Na_2CO_3 produced the lowest emissions to air but not to water.	1 kg of the selected PCM	Cradle to gate	not available
Nienborg et al., 2018	Life Cycle Assessment of thermal energy storage materials and components.	GWP and Primary energy demand Paraffins: Cooling: 40 to 70 times higher than water 80 to 130 times higher for heating Salt hydrates Cooling - SP21EK: 12 times higher than water. Heating - SP58: 80 times higher than water	1 kJ material storage capacity	Cradle to grave approach	GWP and PE consumption
Wang et al, 2021	Robust multi-objective optimization with life cycle assessment of hybrid solar combined cooling, heating and power system	GWP Hybrid PV/T CCHP system (model): 630,045 $kgCO_{2eq}$.	not available	not available	GWP, REP, AP
Zsembinszki et al, 2021	Life Cycle Assessment of an Innovative Compact Hybrid Electrical-Thermal Storage System for Residential Buildings in Mediterranean Climate	GWP100 Reference/conventional system: 1123 kg CO_{2eq}/ m^2 (operation) Innovative system: 350 kg CO_{2eq}/ m^2 (operation) Reference/conventional system: 59 kg CO_{2eq}/ m^2 (manufacturing and disposal) Innovative system: 314 kg CO_{2eq}/ m^2 (manufacturing and disposal stages) Contribution of module in the total impact (innovation system): latent TES system 29% sorption storage 27% solar field 21%	1 m^2 of living floor	Cradle to grave approach	Midpoint and endpoint impact categories (22 categories) and GWP (20 years and 100 years).

2.2   Methodology

The life cycle assessment (LCA) approach was developed taking into consideration the potential environmental benefits from the implementation of the MiniStor system for heating, cooling, domestic hot water heating and energy storage. The possible environmental effects (emissions, resource consumption) of the MiniStor system were examined at every phase of its life cycle with the aim to accurately assess its carbon footprint. The LCA was conducted with a thorough model of the MiniStor system developed considering the inputs and outputs of raw materials and the energy flow at each phase.

In this framework the following actions took place:

- Definition of goal and scope of the assessment, the aim and parameters of the evaluation, the functional unit, the system boundaries, the impact categories that are evaluated and limitations and assumptions
- Compilation of components data relevant to system inputs and outputs (LCI)
- Evaluation of the inputs and outputs listed in the inventory in relation to any potential environmental effects.
- Analysis of the outcomes of the inventory assessment and impact evaluation stages aligning with the study's objectives (LCIA) (Figure 1).
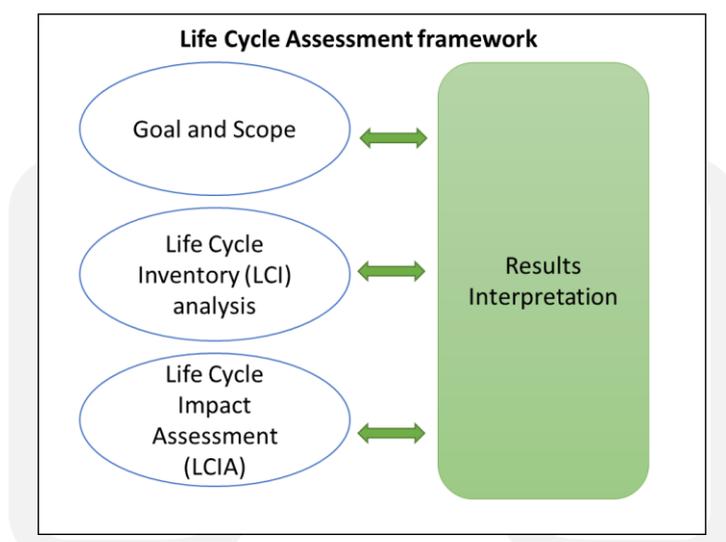
Figure 1. Schematic presentation of Life Cycle Assessment framework (ISO 14040; 2006)

The approach for conducting the LCA was achieved through the commercial software SimaPro v9.3.0.3 and the integrated database Ecoinvent v3.5 (with cut-off allocation). Compiled data can be categorized into primary and secondary data. Primary data encompasses information obtained from the project technology providers (ENDEF, PSYCTOTHERM, SUNAMP) and the technical specifications provided by on-site measurements (e.g. energy demand) or the demo sites operators such as lifetime, raw materials of construction of the various solar system components, (e.g. PVT, FPC, electrical storage system (battery and solar inverter). On the other hand, as the acquisition of primary data was not possible or complete in some cases, secondary data were retrieved from the literature or the Ecoinvent database v3.5 such as compressor data or heat pump data, electricity mix of each country, etc. As far as it concerns the electricity mix, the Ecoinvent electricity mix low voltage is adopted. Data were predominantly *"RER: rest of Europe"* obtained from the Ecoinvent database, while in case of unavailability of those data then global data were chosen as alternatives ("GLO: globally or RoW: Rest of World).

The environmental profile of MiniStor System was expressed using the global method IMPACT World+ Midpoint V1.01, considering eighteen environmental impact categories:

1. Climate Change with long term and short term
2. Fossil and nuclear energy use
3. Mineral resources use
4. Photochemical oxidant formation
5. Ozone layer depletion
6. Freshwater ecotoxicity
7. Human toxicity cancer
8. Human toxicity non-cancer
9. Freshwater acidification
10. Terrestrial acidification
11. Freshwater eutrophication
12. Marine eutrophication
13. Particulate matter formation
14. Ionizing radiation
15. Land transformation biodiversity
16. Land occupation biodiversity
17. Water scarcity

The IMPACT World+ method was used to follow a globally regionalized approach as it allows the assessment of the system's life cycle regardless of the geographic region. Many others impact assessment methods evaluate the impact of a system based only on a specific region. For instance, methods like Eco-indicator 99, CML, ReCiPe, EDIP, IMPACT 2002+, and EPS are tailored to Western European conditions, LIME 2.0 to Japanese conditions and LUCAS to Canadian conditions (Idzikowski et al, 2021). IMPACT World+ is an update of the previous impact evaluation methods IMPACT 2002+, LUCAS, and EDIP methods and is based on a midpoint-damage framework (Bulle et al, 2019). This method enables the estimation of environmental impact with reduced model uncertainty and increased environmental relevance. IMPACT World+ endpoint V1.01 was used combining characterization, damage assessment, normalization, weighting and single score assessment (damage to human health and ecosystem quality). The use of a single score simplified the complexity of multiple impact indicators, acknowledging at the same time their interconnections.

2.3 Goal and Scope of LCA

The goal of the LCA is to study the environmental footprint of MiniStor. The system's environmental impact will be compared to the corresponding one of conventional heating/cooling systems (e.g. heat pump, natural gas or oil-based heating system) typically used in residential buildings. Furthermore, a baseline approach is developed to be used as a reference point for comparing the environmental impacts of MiniStor. All the outcomes will be used to access the system's sustainability and facilitate relevant stakeholders.

The scope of LCA includes several aspects such as the impact categories that will be evaluated, the functional unit that will be, the system boundaries as well as assumptions. The LCA follows the international standards ISO 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006) and considered the whole life cycle, known as cradle-to-grave life cycle assessment.

The MiniStor system's lifetime is estimated to exceed 20 years (*as stated in the Grant Agreement*), therefore, a lifetime of 20 years is considered for the LCA.

The outcomes of the eighteen Midpoint impact category indicators were computed, with a particular focus on the evaluation of the following three impact categories specified in the description of Task 7.2, that are:

- long-term climate change (kg CO_{2eq});

- fossil and nuclear energy use (MJ derived) and
- water scarcity (m^3 world$_{eq}$).

An assumption on modes of transportation and distances for components from the manufacturers to their assembly and installation at the site location was established to assess the impact of transportation on the overall evaluation. Maintenance of MiniStor was excluded from the analysis as it contributes minimally compared to other impacts during the operation phase (Herrando et al, 2022). Moreover, concerning the end-of-life phase, the metal parts are considered recycled while the rest of the materials are disposed of in a landfill.

For the analysis the MiniStor system installed in Thessaloniki is used as reference, while 8 different locations (with suitable building typologies) are analyzed, and their results are provided in the Annex. Differences among the demonstration sites were observed regarding the operation phase in the energy consumption of each location as well as in the MiniStor energy coverage.

2.4 Functional unit and system boundaries

As functional unit the "*coverage of the annual needs of a standard typical building*" encompassing the fulfillment of the building's heating, cooling, hot water and electricity demands was considered similarly with other studies in the literature (Hayatina et al, 2023; Herrando et al, 2022; Guillén-Lambea et al, 2021; Martinopoulos, 2020; Martinopoulos, 2018). The system boundaries determined include the relevant activities in the manufacturing, installation and assembly of components, transportation, operation and end of life phases of the LCA. The LCA system boundaries are graphically illustrated in Figure 2. The following life cycle stages were considered while drawing the system boundaries:

- <u>Manufacturing phase</u>: includes the extraction of raw materials, the manufacture of components, as well as the energy needed during installation of the components (eg. machinery works). Moreover, the processes involved during the manufacturing phase such as metal working are taken into consideration. Metal working involves the manufacturing steps that transform a semi-manufactured product into a finished product. It incorporates average values for machine processing, as well as the infrastructure and operation of the factory. Additionally, an extra input of each metal component (eg. aluminium, stainless steel etc) is considered due to losses during the process.
- <u>Transportation</u>: comprises modes and distances of the transportation from the manufacturer location to the installation site.
- <u>Operation phase</u>: consists of all actions necessary to run the system. It encompasses the use of water, electricity, and other fossil fuels.
- <u>End of life phase</u>: entails dismantling of the MiniStor system components and then transporting them to a landfill or to a recycling sorting facility.

3 Life Cycle Assessment

The life cycle assessment (LCA) conducted considered the MiniStor system as comprising six major sub-systems, each one encompassing specific component (Figure 3).

MiniStor system is separated to the following **six major sub-systems**:

1. Solar assisted unit: It includes the PVT and the FPC along with the hot water tank (buffer tank) and the incorporated auxiliary heater.
2. TCM reactor which contains the ammoniated-based salts or ammonia
3. Ammonia loop, that includes the ammonia compressor, condenser, evaporator and a storage tank of liquid ammonia
4. Heat pump evaporator and condenser
5. PCM vessels that include the appropriate phase change material.

6. Battery Energy Storage system, including hybrid solar inverter and the battery/ies used for storing the electrical energy produced by the PVTs.
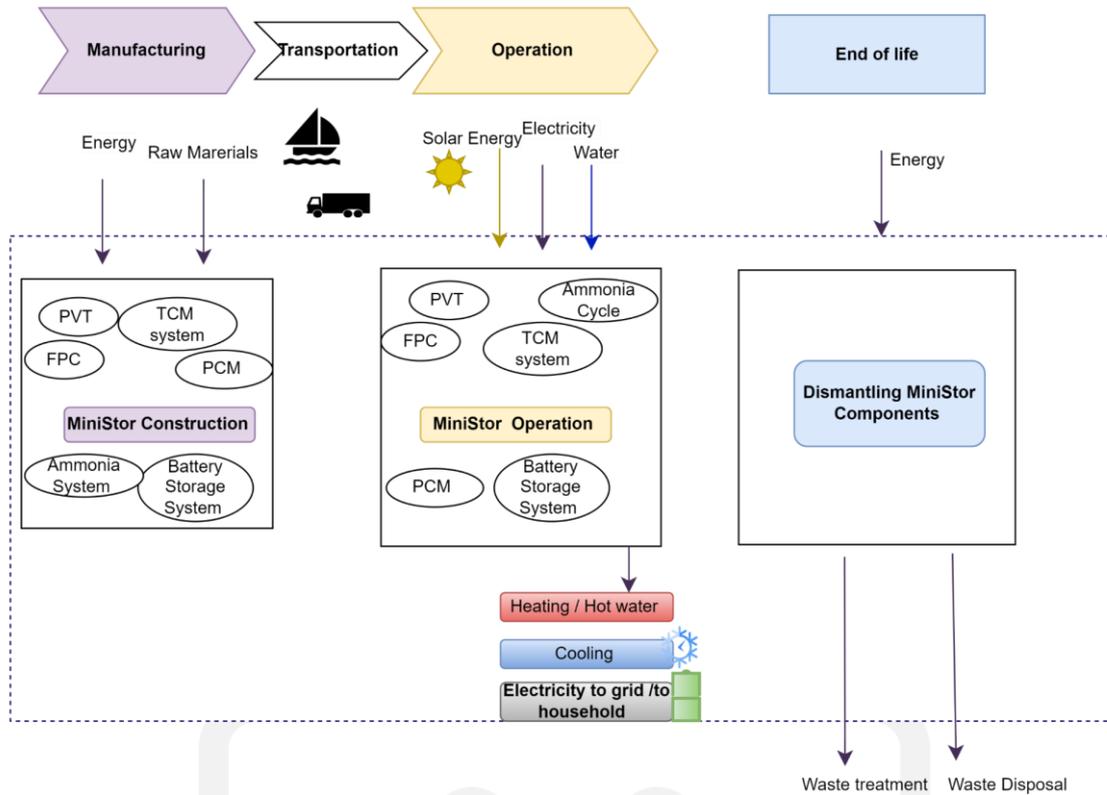
Figure 2. MiniStor System boundaries illustrating separately each phase of LCA
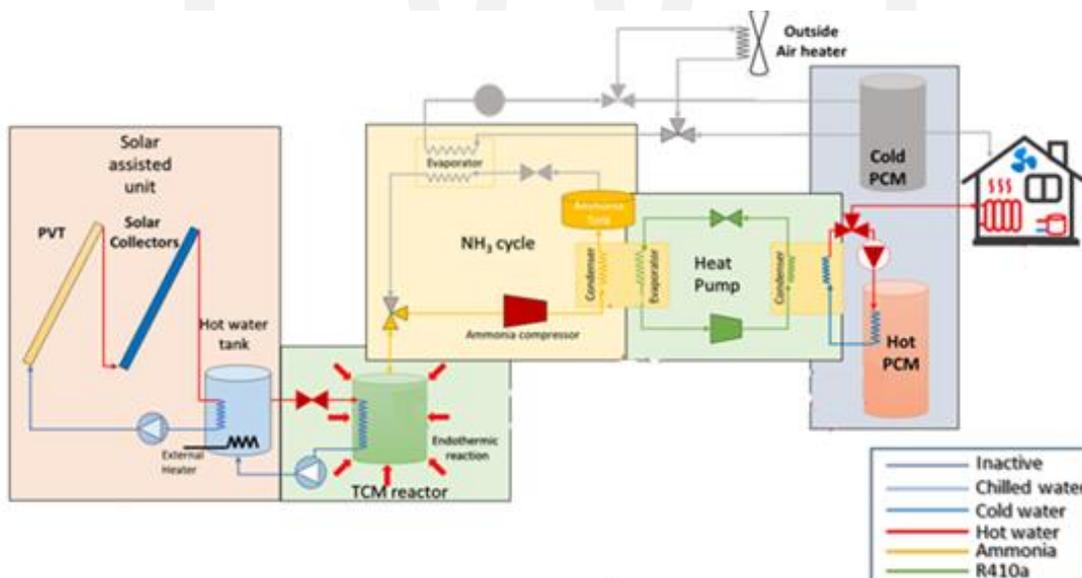
Figure 3. The major sub-systems of MiniStor (Deliverable 3.5)

Furthermore, MiniStor is divided into three main groups to facilitate the calculations and visualizations of the materials mass balance as well as the comparisons among the demo sites.

1. **Solar area** including the PVT and FPC.
2. **MiniStor main system** includes the metallic container and all the equipment that it houses (hot water tank (buffer tank) with heater, ammonia compressor, the HP, ammonia condenser, ammonia evaporator, heat transfer fluid, lubricating oil, the TCM reactor, the PCM vessel and the BESS system).
3. **The remaining infrastructure** encompasses the electrical cables, the piping system and the metallic structures to support the solar collectors.

3.1 Life Cycle Inventory

Life Cycle Inventory encompasses, as already mentioned, the mass of the materials used and the required energy (and emissions) during manufacturing and installation. LCI data derived from the manufacturer of the components, the technical brochures of components and in case there was deficiency of data on materials, the literature and Ecoinvent database was used.

In Annex I, the components are grouped, and their derived data source is presented. For each sub-system the LCI is described, while detailed tables of LCI of each component and its accounted materials are included in **¡Error! No se encuentra el origen de la referencia.** and **¡Error! No se encuentra el origen de la referencia.**. It is worth mentioning that the process of conversion of the various raw materials into the various semi-manufactured goods was also taken into consideration.

3.1.1 Manufacturing phase

The process followed for each of the six sub systems is presented in the following paragraphs.

Solar assisted unit

- Photovoltaic thermal collectors
- Flat Plate Collectors
- Hot water tank (buffer tank) with heater

The raw materials used in the component's construction are displayed in
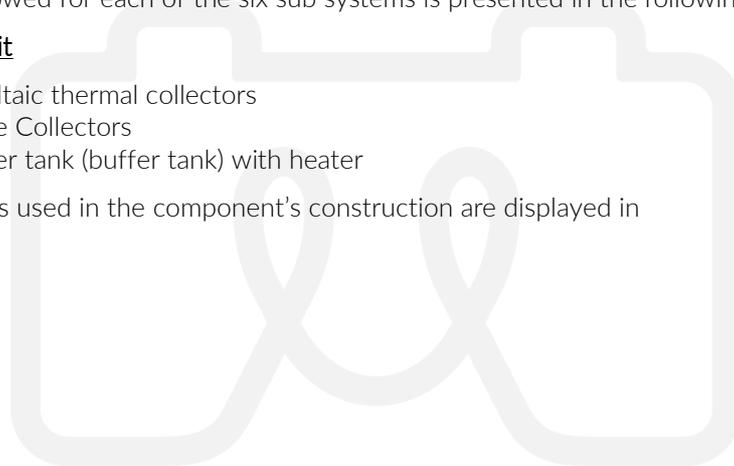
Table 2 and Table 3. The dataset involves the activities that produce the material until the material is supplied to consumers. Transport is included in the case of all raw materials. Product losses are considered negligible during transportation. Furthermore, the data set encompasses the manufacturing procedures necessary to build a semi-manufactured product and turn it into a final product. It includes average values for the processing of machines as well as the factory infrastructure and operation. Data was derived from ENDEF (primary). In Figure 4, Figure 5 and Figure 6 the mass balance of the materials utilized for the solar field in addition to the remaining infrastructure (electrical cables, piping system, metallic structures to support the solar collectors) is illustrated.

Table 2. Life Cycle Inventory during the manufacturing stage for the solar area (per 1 PVT and 1 FPC) and the buffer tank (solar water tank with auxiliary heater)

		Solar Area		Buffer tank	
Raw materials	Unit	PVT	FPC	Hot water tank	Auxiliary heater
Glass	kg	26.17	19.72		
Silicon	kg	0.69			
Silver paste	kg	0.003			
Copper	kg	9.37	5.68	1.38	0.24
Aluminium	kg	7.16	10.52		
Rock wool	kg	2.32			
Stone wool	kg		5.06		
Synthetic rubber	kg		0.2		
Polypropylene	kg	0.008			
Polyurethane	kg			2.68	
PVC	kg			0.1	0.01
Steel	kg			20.84	
Metal working, average for chromium steel product manufacturing				20.84	
Metal working, average for copper processing	kg	9.37	5.68	1.38	0.24
Metal working, average for aluminium processing	kg	7.16	10.52		
Electricity consumption during the installation of the component					
Electricity, medium voltage	kWh	0.14	0.11	0.23	0.01

Table 3. Life Cycle Inventory during manufacturing stage for the remaining infrastructure

		Remaining Infrastructure		
Raw materials	Unit	Metallic structures to support the solar collectors	Piping	Electrical cables
Copper	kg		50	11.05
Aluminium	kg	100		
Steel	kg	80		
Elastomere foam	kg		14	
Wire drawing, copper	kg			11.05
Polyethylene	kg			4.75
Extrusion, plastic pipes	kg			4.75
Metal working, for copper processing	kg		50	11.05
Metal working, for aluminium processing	kg	100		
Metal working, for steel processing		80		
Electricity consumption during the installation of the component				
Electricity, medium voltage	kWh	3.75		
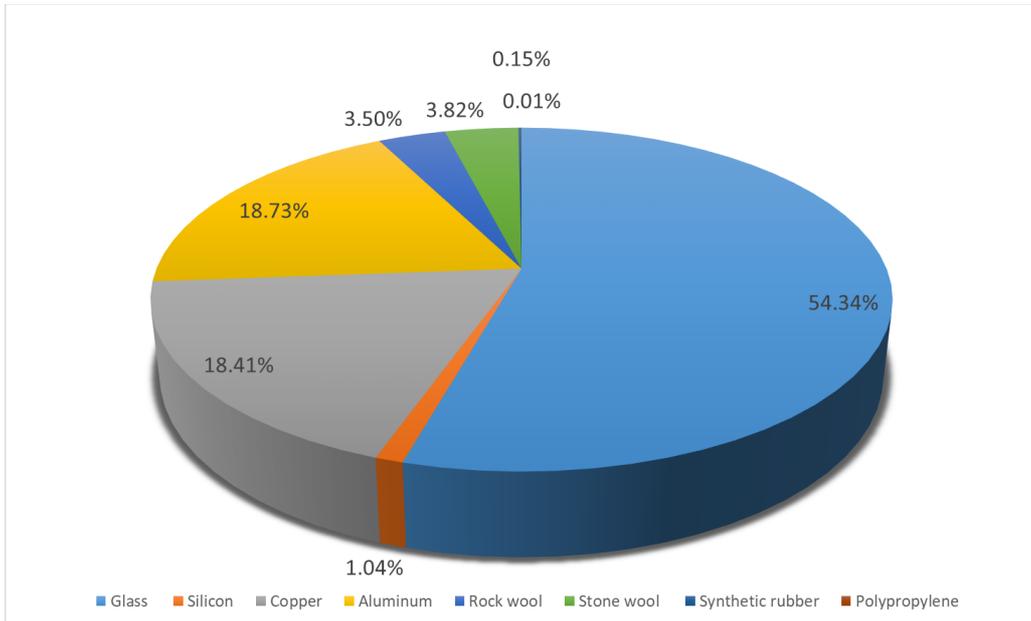
Figure 4. Mass balance of the solar area subsystem
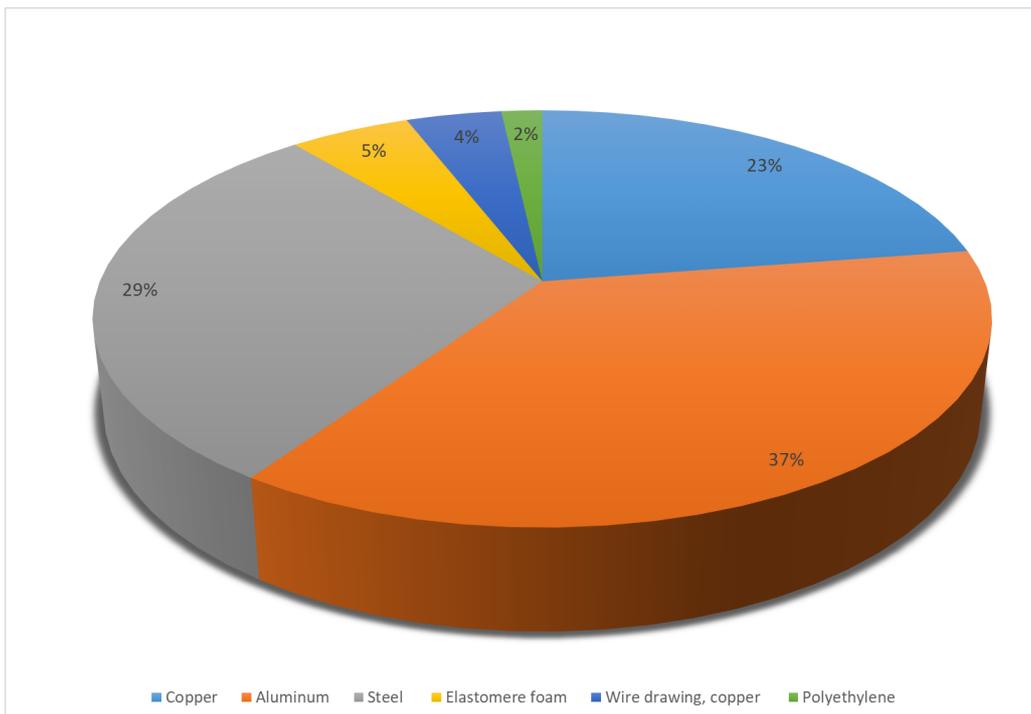
Figure 5. Mass balance of the materials utilized for the remaining infrastructure (*electrical cables, piping system and metallic structures to support the solar collectors*)
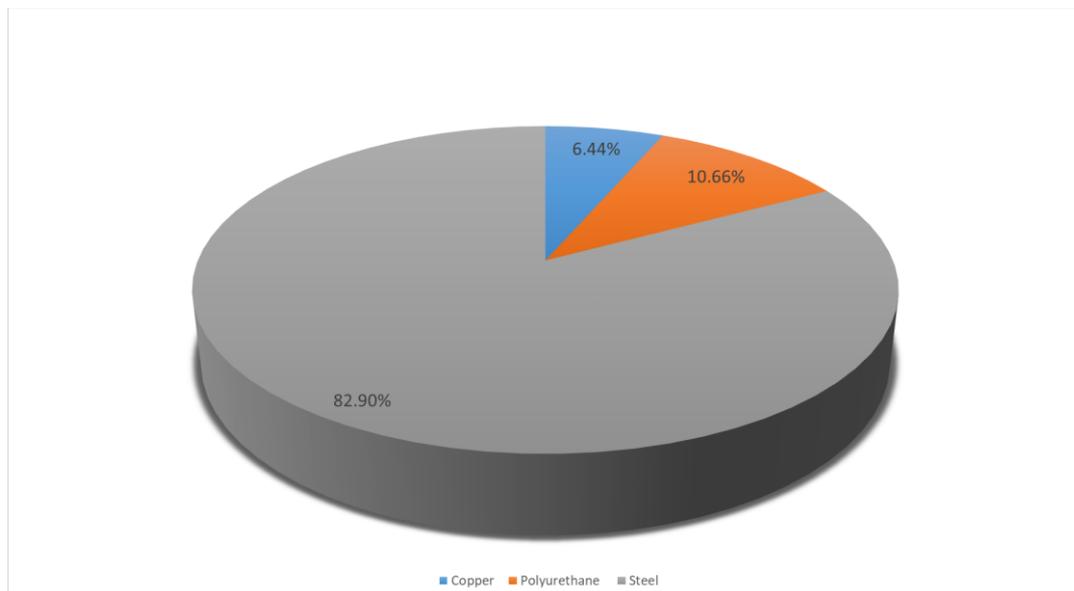
Figure 6. Mass balance of the materials utilized for the buffer tank

Thermochemical material reactor (TCM)

The MiniStor system uses thermochemical heat storage (TCM) based on a $CaCl_2$-NH_3 cycle. The TCM reactor utilizes a 'shell and tube' design and consists of tubes each containing reactive materials, situated within a shell such that the heat transfer fluid circulates perpendicularly to the tubes. The TCM reactor is a stainless-steel storage vessel in which energy is stored in chemical form. The thermochemical reactor is composed of 7 tubes with a length of 1.25 m each and diameter of 114.3 mm. The total mass of stainless steel (Shell + 6 baffles + reactor tubes) is 120 kg, (95 kg, 3 kg and 22 kg, respectively). Moreover, the shell of the TCM storage unit is 0.4 m diameter and 1.5 m length. The reactor tubes (4"OD Sch5S) have the following characteristics, an outside diameter of 0.114 m and wall thickness of 0.003m. Additionally, based on SOFIGRAM, the insulation of the TCM consists of 10 kg of Armaflex.

The volume content of the heat transfer fluid in the TCM shell is 40lt, the mass of the TCM material is 41.7 kg where 35.5kg is the mass of the salt (anhydrous $CaCl_2$), and 6.2 kg the mass of the graphite. The quantity of ammonia absorbed (cycle ammonia mass during the charging phase) is equal to 23.7 kg.

The total mass of the shell and tube reactor when the salt is fully charged (@ $CaCl_2 \bullet 8NH_3$) and filled with water is 190 kg (approx.) (Deliverable 4.3). In the whole MiniStor System the quantity of heat transfer fluid (HTF) circulated in the pipes is a mixture of water/ propylene glycol 25% of 245 lt. Figure 7 illustrates the mass balance of the infrastructure materials of TCM.
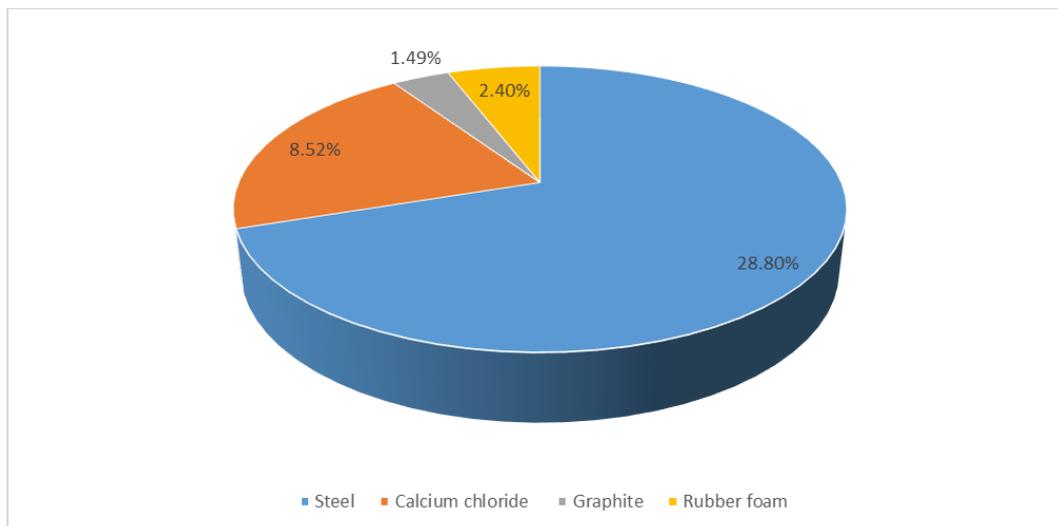
Figure 7. Mass balance of the materials of the thermochemical reactor

Ammonia cycle

The ammonia cycle includes an ammonia compressor, condenser, evaporator and a storage tank of liquid ammonia. The compressor model "7-DLRC-3" with a nominal heating capacity of 4 kW, which is the smallest model manufactured by Frigopol, is used in MiniStor. This compressor is a semi-hermetic type of compressor with a separating hood to reduce ammonia leakage risks. Based on technical data from the manufacturer the net weight is 41 kg and the lubricating oil quantity is 0.7 l (MOBIL SHC 226) a synthetic hydrocarbon polyalphaolefin (PAO) fluids free of wax, which exhibits exceptional resilience to oxidative and thermal degradation.

Ammonia compressor's dataset includes the materials and machining processes needed to produce a compressor. Also, disposal is included. However, since the manufacturer data are not available, for the inventory a screw-type air compressor of 4 kW was selected from the Ecoinvent database. Dataset includes the materials and machining processes needed to produce the compressor.

In addition, regarding the lubricating oil an Ecoinvent dataset was also selected, which represents the production of 1 kg of liquid lubricating oil, including the input materials (also additives), energy uses, infrastructure and emissions. As the ammonia compressor uses a synthetic oil lubricant that is not miscible with ammonia, an oil separator must be installed on the discharge line. The OSC COLD Company (model RTX) provides the oil separator with design pressure and minimum temperature 45 bar and -10 °C, respectively. For the inventory, data from its brochure were used.

Ammonia condenser

The ammonia condenser used in MiniStor is an ammonia condenser with a water heat exchanger. Based on Deliverable 4.3, the ammonia condenser is a plate heat exchanger manufactured by Spirec. The plate material is stainless steel 316L with nickel brazing. Heat exchange surface is 0.347 m² and it has a maximum nominal working pressure of 70 bar in the ammonia circuit and a maximum nominal working pressure of 30 bar in the water-cooling circuit. The ammonia condenser weight according to the manufacturer is 4.64 kg.

Ammonia Evaporator

Concerning the evaporator, the inventory of the manufacturer (Spirec, model: EC.07.48.T) was used. The raw material of Spiral plate heat exchangers for R410A is stainless steel AISI 316L welded without gaskets. Stainless steel AISI 316L typically contains 16–18% chromium, 10–14% nickel and 2–3% molybdenum. Stainless steel 316 is more resistant to corrosion than other grades of metal when molybdenum is added. Stainless steel 18/8 was selected as raw material as its principal alloy

composition is 18% chromium and 8% nickel content by mass. The evaporator weight is assumed to be around 4.64 kg.

Liquid ammonia tank

The maximum amount of ammonia in liquid form that must be able to be stored in the liquid reservoir at 45 °C, has a volume of 49.8 liters, although the estimated cycled volume under typical working conditions is only 39.2 liters (or 25.2 kg). A carbon steel vessel with a capacity of 57 liters (useful cycling volume 49.8 lt) has been selected. Based on the manufacturer, the tank's weight is 35.41 kg and there is no insulation material. Figure 8 illustrates the raw materials for the ammonia cycle's components.

Heat pump

A heat pump including a compressor, a condenser and a refrigerant (R410a) is used in the system. Based on technical data the refrigerant was 0.6 kg and the weight of the heat pump is 12kg. R410a is a refrigerant mix consisting of two main components, difluoromethane (R-32) which is a hydrofluorocarbon (HFC) refrigerant with the chemical formula CH_2F_2 and a pentafluoroethane (R-125) which is an HFC refrigerant with the chemical formula C_2HF_5. A relevant refrigerant was used to estimate the impact of heat pump infrastructure.

As there was no detailed data for the inventory of the heat pump, the module of "Heat pump, 30kW" from the Ecoinvent database was selected. This includes the most important materials used for production, transport of these materials, and energy needed for production. It includes emissions of refrigerant during production and scrapping. It does not include emissions during operation. The lifetime for the heat pump is assumed to be 20 years.

The infrastructure of "Heat pump, 30kW" was modified to the nominal capacity of 2.1 kW based on PSYCTOTHERM information. The materials of the heat pump are depicted in Figure 9.
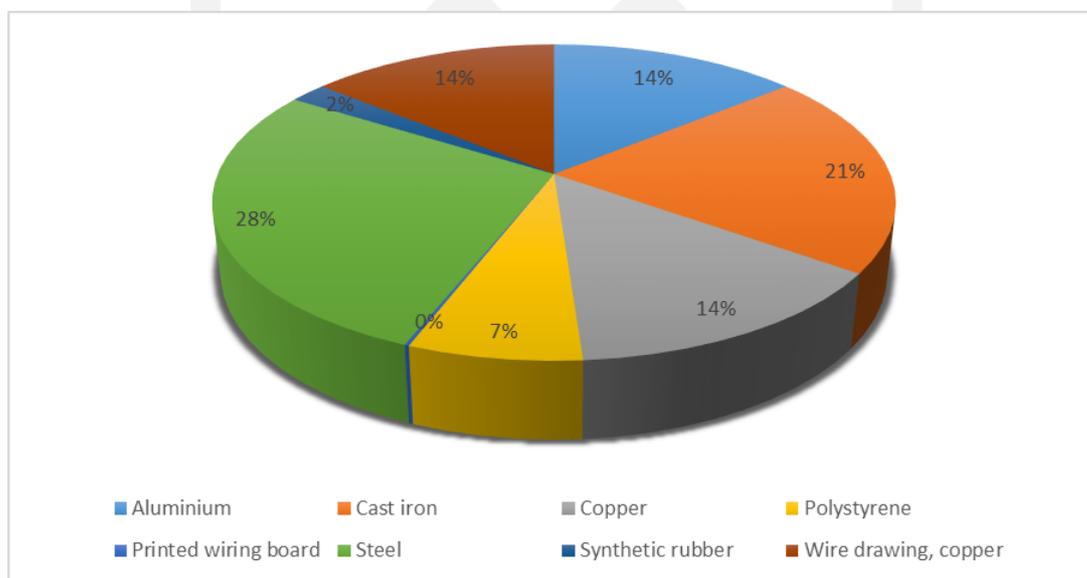
Figure 8. Mass balance of the materials of all the components comprising the ammonia cycle
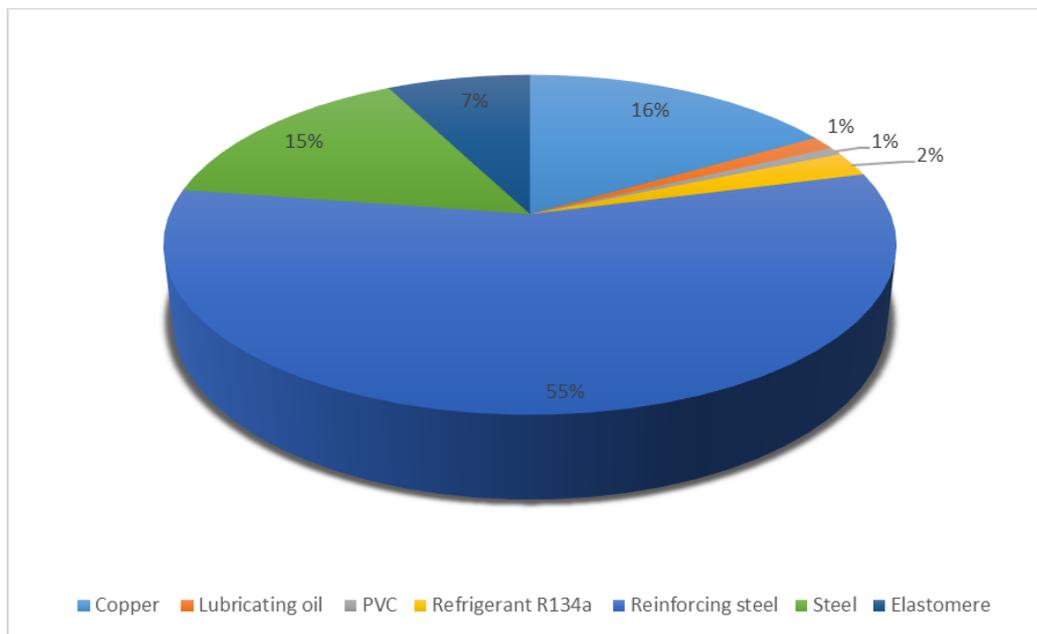
Figure 9. Mass balance of the materials of the heat pump

PCM vessels

The hot and cold PCM storages use components based on the UniQ Heat Batteries (Sunamp). MiniStor system implements a UniQ3 heat battery for space heating (3.5 kWh), a UniQ6 for domestic hot water (7 kWh), and one UniQ6 battery for the cold PCM storage (5 kWh cold storage capacity). Heat exchangers in Sunamp's UniQ line of heat batteries are immersed in PCM and housed in polypropylene cases for hot PCM and polyethylene cases for cold PCM. Insulation surrounds the casing before an outside aluminum case is added (Deliverable 4.3). The phase change material of hot PCM has the commercial name SU-58 which represents the Sodium Acetate Trihydrate compound. The total quantity of SU-58 used in the vessel is calculated at 21.97 kg considering the specifications of the manufacturer (Sunamp) for the UniQ3 heat battery. Table 4 contains the reactants of Sodium Acetate Trihydrate and their respective quantities.

Table 4. Constituents of substances yielding 1 kg of SU-58

Materials/fuels	Unit	Value
Acetic acid, at plant/kg/RNA	kg	0.44
Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	kg	0.29
Water, deionised {RoW}| market for water, deionised | Cut-off, U	kg	0.26

The phase change material of cold PCM has the commercial name SU-11 which represents the dimethyl adipate compound. This can be produced by the esterification of adipic acid with methanol. Table 5 contains the reactants of dimethyl adipate and their respective quantities. The total quantity of SU-11 used in vessel is calculated at 59.06 kg considering the specifications of the manufacturer (SUNAMP) for the UniQ6 heat battery. Table 6 presents a comparison of the materials' composition of each PCM vessel and Figure 10 illustrates the mass balance of PCM materials in addition to the heat batteries for space heating, for DHW and cooling.

Table 5. Constituents of substances yielding 1 kg of SU-11

Materials/fuels	Unit	
Adipic acid {GLO}| market for | Cut-off, U	kg	0.84
Methanol {GLO}| market for | Cut-off, U	kg	0.36

Table 6. Composition materials of the hot and cold PCM

Hot PCM	Cold PCM
Heat Exchanger	Heat Exchanger
PCM – SU-58	PCM – SU-11
Polypropylene case (plastic cell)	Polyethylene case (plastic cell)
Glass wool mat	Glass wool mat
Aluminium (outer case)	Aluminium (outer case)

Battery Energy Storage System (BESS)

The electricity generated by the PVT panels is stored by the PVT electrical system. The system's primary parts encompass the lithium-ion battery-based electrical storage system, the hybrid solar inverter, the electrical panel, and the wiring.

Data regarding the Li-ion Battery (Lithium-Iron-Phosphate-LFP), *BYD LVS 5.1*, is not available by the manufacturer. However, a Li-ion battery cell NMC811 was selected from the Ecoinvent database which represents a Li-ion battery cell comprised of nickel-manganese-cobalt 811 (NMC811) cathode and silicon coated graphite-based anode. Based on the Ecoinvent database the specific energy capacity of the Li-ion Battery cell NMC811cell is 0.209 kWh/kg cell. Moreover, the manufacturing of Li-ion battery cells includes not only the production of the battery cell components but also the materials for other components (external case, tabs, etc.) entering the factory gate. This battery was adjusted to the component weight of 91 kg matching the weight of the battery based on the manufacturer's technical specifications. Figure 11 depicts the mass balance of the materials of the BESS. Regarding the hybrid solar inverter, data has been derived from the manufacturer.
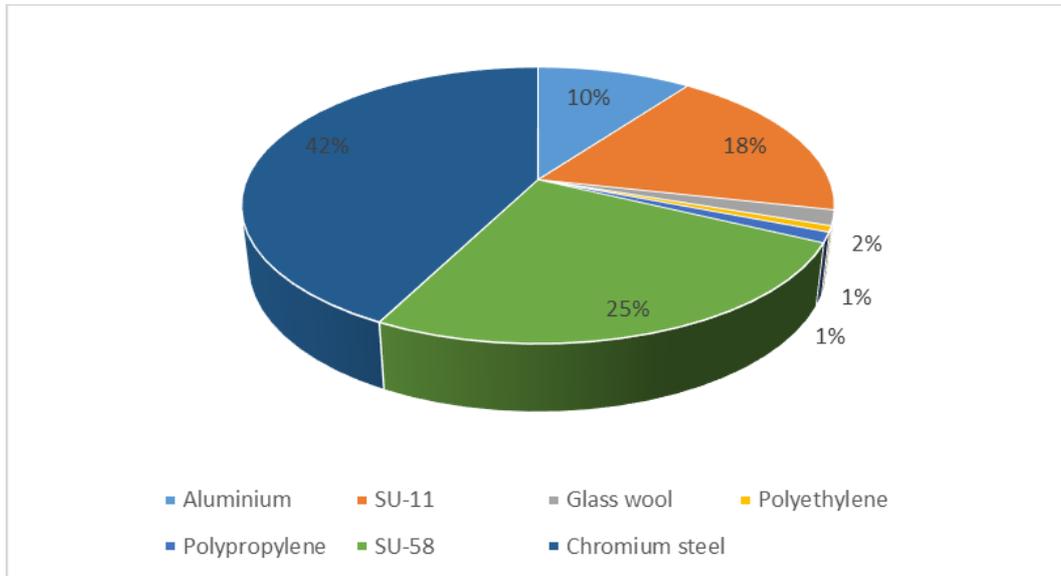
Figure 10. Mass balance of the materials of hot and cold PCM as well as the domestic hot water heat battery
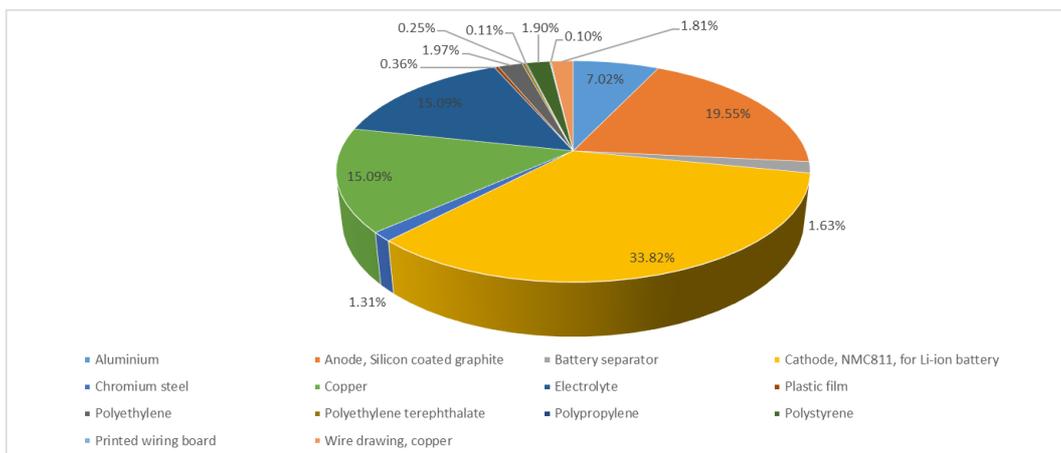
Figure 11. Mass balance of the materials of the Battery Energy Storage System (BESS)

Control Unit

All the electronic equipment is gathered in a stainless-steel box weighing 90kg with 3.5 kg of plastic (cables are included). Annex I Table 18 presents in detail all the inventory data.

Metallic container

A 3-meter-long container houses the components of MiniStor system with external connections to the building. This design choice has the advantage of making the system assembly and installation on site as simple as possible while maintaining the isolation and maintenance access required. MiniStor metallic container, houses the following components: the hot water buffer tank, the ammonia liquid tank, water to water heat pump (HP), PCM storage for DHW, PCM storage for heating, PCM storage for cooling, TCM reactor, NH_3 compressor, NH_3 condenser, evaporator and oil separator. Based on manufacturer's data the container is made of stainless steel and PVC and weighs 840 kg.

In the MiniStor system, four pumps are used, two with a nominal capacity of 42W and another two with a nominal capacity of 56W. Values from the database of Ecoinvent were adapted properly. The materials of the MiniStor system with their percentage breakdown and with values greater than 2 %, are depicted in Figure 12. Chromium steel (45.6%) is the dominant component of the MiniStor system following significant percentages of steel (10.1%), which provides additional mechanical support, and water (9.2%) which as a heat transfer fluid is necessary for the system's functionality. The phase change materials, SU-11 and SU-58, which contribute to the system's heat storage corresponding to the 4.0% and 2.9% of the system. The remaining 10.8% of the system is classified as "others," which includes a variety of minor components critical to its general operation.
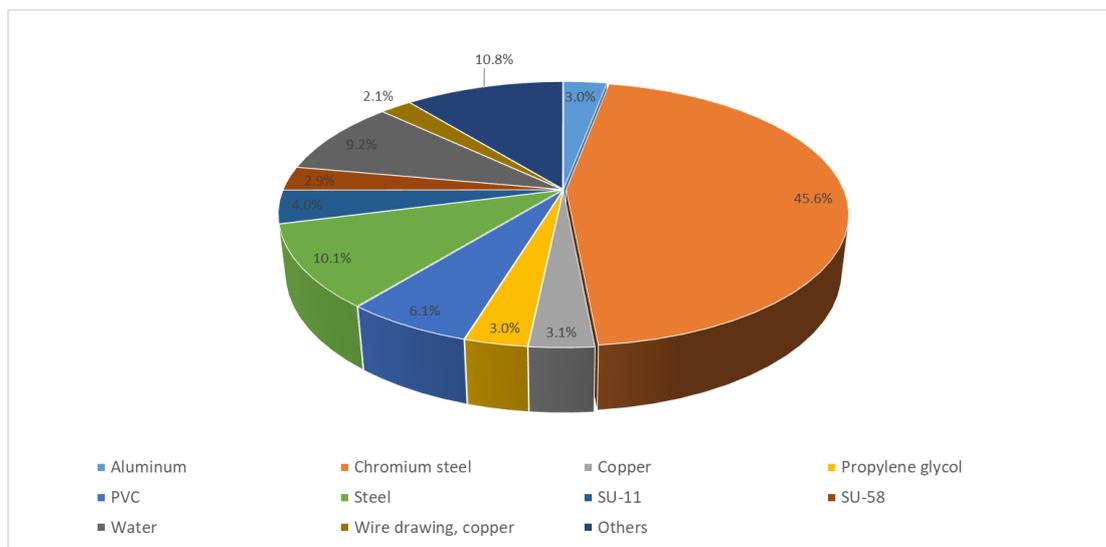
Figure 12. Pie chart of mass balance of the MiniStor System's raw materials, ("others" represent materials less than 2%)

3.1.2   Transportation

The estimations of indicative transportation involved in the assembly of the MiniStor components have been considered in this step. The distance from the manufacturers' site to the installation site (Thessaloniki demo site) is also considered. For instance, the components of Thessaloniki's solar array (10 PVTs and 5 FPCs) are constructed in Spain and transported to Thessaloniki via a 7.5tn freight truck. The unit is expressed in tkm (ton.kilometer) in which the weight of the component is multiplied by the distance travelled. Two modes of transportation considered: truck and ship. The processes selected by the Ecoinvent database concern transportation of freight by lorry and container ship.

Table 7 presents the transportation data.

Table 7. Transportation data of main MiniStor components from manufacturer to the Thessaloniki demo site

Component	Travelled distance	Transport, freight, lorry (tkm)	Transport, freight, sea, container ship (tkm)
PVT (n=10)	2185 km (Spain to Greece)	999	
FPC (n=5)	2185 km (Spain to Greece)	450	
Hot water tank	1067 km (Italy to Greece)	27	
TCM	2508 km (France to Greece)	468	
Insulation	1979 km (Germany to Greece)	20	
Li-ion Battery cell	18353 km (China to Greece)		1970
Hybrid solar inverter	2897 km (Austria to Greece)	8	37

3.1.3   Operation phase

The lifetime of the MiniStor system is assumed to be 20 years, as in the Grant Agreement, although based on the components used, its useful life is expected to be considerably longer. The recommended lifetime differs among the components in the life cycle assessment of MiniStor system. It is noteworthy that the lifetime is typically dependent on the components' quality, operating conditions, and maintenance procedures.

The lifetime of the PVT and FPC is considered at 20-25 years (Weiss and Spörk-Dür, 2023; IEA, 2016). Their support structure lifetime is considered between 30 and 60 years for ground mount installations on metal supports, and 30 years for roof-top and façade installations. For hot water tanks (buffer tank) a lifetime of 20-30 years and for the external (back-up) heater a lifetime of 20 years is usually considered.

The lifetime of the TCM reactor is considered at 20 years (IRENA; 2020).

The lifetime of the ammonia compressor is considered 15 to 20 years *(based on manufacturer data lifetime is 100,000+ hours (10+ years)[1]* while based on the lubricating oil manufacturer (Kluber) the lubrication oil for rotary screw compressors can extent to 12,000 hours. For 20 years (175,200 hours) then 14.6 items are needed (15 are considered).

Ammonia condensers and evaporators are heat exchangers which are typically engineered with an anticipated lifespan ranging from 20 to 25 years[2] and the storage tank of liquid ammonia is considered 20 to 30 years.

The HP lifetime is considered 20 years as seen in the Ecoinvent database.

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[1] nigen.com
[2] gesmex.com

PCM vessels and specifically the PCM battery for heating, cooling and domestic hot water are considered as having a lifetime of 20 years. Since MiniStor system lifetime is 20 years, one PCM vessel is required.

Hybrid solar inverter lifetime varies between 10-15 years based on manufacturers[3].

Regarding the lithium-ion battery using the technology of LFP (Lithium-Iron-Phosphate) the Cycle life>6000 times with 95% battery roundtrip efficiency based on manufacturer. Moreover, the longevity of Li-ion batteries is constrained by undesired side reactions, resulting in capacity decline and elevated cell impedance. Battery chemistry and BESS operation significantly influence lifespan and can be considered 10 years (Wankmüller et al, 2017).

Considering that the main components of the battery system have 10 years' lifetime each, two batteries and two inverters are necessary during the 20year-MiniStor lifetime.

To sum up, the components that compose the MiniStor system and their lifetime are depicted in Table 8.

Table 8. Lifetime of each component of 20y MiniStor system and the number of replacements

Components	Lifetime (y)	Replacement
PVT /FCP	20-25	None
TCM reactor	20	None
Ammonia compressor	15-20 *(considered 20)*	None
Ammonia condenser & evaporator	20-25 *(considered 20)*	None
Liquid ammonia storage tank	20-30 *(considered 20)*	None
Heat pump	20	None
PCM vessels	20	None
Hybrid solar inverter	10-15 *(considered 10)*	Once
BESS	10	Once

3.1.3.1   Electricity mix for the various cases

MiniStor system operates using renewable energy and producing thermal and cooling energy. In case that the renewable energy is inadequate then the electricity mix is used. For the demo site of Thessaloniki and the eight replication sites the electricity mix used was based on geographical region of each site. The examined replication sites are Paris (France), Krakow (Poland), Berlin and Hamburg (Germany), Bergen (Norway), Larnaca (Cyprus), Athens (Greece) and Rome (Italy). Therefore, the electricity mixes of Greece, of Germany, Norway, Cyprus, and Italy are considered with data based on Ecoinvent database.

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[3] solargrid.co, .beny.com

Table 9 presents the low electricity impact of the countries where the replication sites are installed. Electricity is a critical input for the MiniStor System since it is necessary to supply the electrical demand of the internal elements of the system, such as the internal heat pumps, the auxiliary heater, and the air cooler in the solar thermal circuit.

Table 9. Impact of low voltage electricity mix for the demo and the replication sites.

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_2 eq	MJ deprived	m^3 world eq
Thessaloniki	7.55E-01	1.19E+01	2.30E-01
Paris	8.41E-02	1.20E+01	3.60E-02
Krakow	1.01E+00	1.22E+01	1.45E-01
Berlin	5.02E-01	7.64E+00	3.22E-02
Hamburg	5.02E-01	7.64E+00	3.22E-02
Bergen	2.61E-02	4.37E-01	2.94E-02
Larnaca	9.67E-01	1.29E+01	6.77E-02
Athens	7.55E-01	1.19E+01	2.30E-01
Rome	3.60E-01	6.40E+00	2.50E-01

3.1.3.2 Replication sites features and requirements

Eight replication sites have been selected for prototype MiniStor operation. The replication sites have the character of residential buildings, single family houses, with realistic consumptions. A detailed description of each house is presented in D6.7, where a methodology for selecting European Union regions with harsh climatic conditions to evaluate the MiniStor system's feasibility is described. The purpose is to assess the system's performance in various European countries and some non-European Union locations identified through the Mission Innovation initiative. Harsh climatic zones, especially those with cold winters and moderate solar radiation, were chosen for analysis based on the Köppen-Geiger climate classification. Key climate types across Europe include temperate, arid, and cold zones, represented in the demo sites of the MiniStor project. The selected regions, including Poland, Greece, Germany, France, Italy, Cyprus and Norway, cover a range of climates from semi-arid to cold zones. The study used Heating Degree Days (HDD) and Cooling Degree Days (CDD) to link climatic data to building energy demands for heating and cooling. For replicating MiniStor, suitable building typologies, mainly single-family homes, were identified through the TABULA web tool. This tool provided data on construction methods, energy efficiency, and typical building characteristics in each region. Energy demands for heating and cooling were calculated using U-values (thermal transmittance) and HDD/CDD data for buildings across cities like Larnaca, Athens, Rome, Paris, Krakow, Bergen, Berlin and Hamburg. According to data acquired from D2.2 and D6.7, Table 10 presents for each site, the floor area and separately the energy demands for space heating and cooling, annually.

Table 10. Annual heating and cooling demands (kWh/y) of the locations considered

City	Country	Floor Area (m^2)	Annual space heating demand (kWh/y)	Annual space cooling demand (kWh/y)
Thessaloniki	Greece	105	8,973	8,520
Paris	France	103	10,476	
Krakow	Poland	187	25,575	
Berlin	Germany	187	19,084	
Hamburg	Germany	187	19,878	
Bergen	Norway	184	16,551	
Larnaca	Cyprus	170	9,812	6,477
Athens	Greece	255	13,618	5,484
Rome	Italy	174	11,146	1,157

Taking into consideration the solar radiation and the location of each site as well as the PV system installed with the assistance of the PVGIS, the annual electricity production of the PV was determined using the PVGIS (Huld, 2012). PVGIS has been developed since 2001 at the European Commission Joint Research Centre's Ispra, Italy. The MiniStor operation covers a portion of the energy requirements of each site. The annual electricity production (kWh/y) from PVGIS, the estimations of the covered annual heating and cooling by MiniStor operation in addition to the electricity requirements of MiniStor separately for each site are illustrated in Table 11 based on data of D3.1. Furthermore, the amount of electricity fed into the grid and the heating and cooling demand that cannot be covered by the MiniStor are displayed in Table 11. Table 12 presents the annual electricity requirements of the demo and the replication sites with and without the operation of the MiniStor. The demo site, along with all the buildings in the replication site, is assumed to use a high-performance Heating, Ventilation, and Air Conditioning (HVAC) system to meet both cooling and heating requirements. The system used for heating and cooling is considered a high-performance HVAC system (heat pump) with Energy Efficiency Ratio (EER) equal to 5 and coefficient of performance (COP) equal to 3, based on manufacturer.

Table 11. Annual energy demands of each site, covered and not covered energy due to MiniStor (D3.1 and D6.7)

City	Annual electricity production (kWh/y)	Annual electricity demand of MiniStor (kWh/y)	Covered heating demand by MiniStor (kWh/y)	Covered cooling demand by MiniStor (kWh/y)	Excess Electricity fed to the grid (kWh/y)	Heating demand remaining (kWh/y)	Cooling demand remaining (kWh/y)
Thessaloniki	4,220	1,955	5,915	3,199	2,265	3,058	5,321
Paris	3,243	3,520	5,186		- 277	5,290	-
Krakow	3,046	3,860	6,670		- 814	18,905	-
Berlin	3,001	3,380	5,675		- 379	13,409	-
Hamburg	2,803	3,390	5,610		- 587	14,268	-
Bergen	2,187	3,585	4,148		- 1,398	12,403	-
Larnaca	4,680	1,005	3,898	3,242	3,675	5,914	3,235
Athens	4,473	1,019	4,456	1,792	3,454	9,162	3,692
Rome	4,245	846	3,931	1,157	3,399	7,215	-

Table 12. Total annual remaining energy demands that cannot be covered by MiniStor (D3.1 and D6.7)

City	Total electricity required annually for the demands without MiniStor (heat pump) (kWh/y)	Total electricity required annually for the demands with MiniStor (heat pump) (kWh/y)
Thessaloniki	4,695	- 181
Paris	3,492	2,040
Krakow	8,525	7,116
Berlin	6,361	4,849
Hamburg	6,626	5,343
Bergen	5,517	5,532
Larnaca	4,566	- 1,057
Athens	5,636	338
Rome	3,947	- 994

3.1.3.3 Baseline Approach

For each demo site, a baseline approach has been developed to be used as a reference point for comparing the environmental impacts of the MiniStor installation and operation. The parameters examined in the LCA framework are related to the current energy system and the energy (heating, cooling, and electricity) demands. Providing an adequate baseline approach is crucial for assessing the effectiveness and benefits of new energy solutions, enabling informed decision-making and tactical preparation.

Calculations - Thessaloniki Demo site

Here, the Thessaloniki demo site is going to be examined and presented. For the baseline scenario, all the loads are covered by the HVAC system (EER=5 and COP=3).

    o   Electricity consumption for cooling

For high-performance HVAC systems, cooling efficiency, EER equals to 5.

Electricity consumption of HVAC = Cooling demands/ EER = 8,520 kWh/y / 5 = 1,704 kWh/y

    o   Electricity consumption for heating

For high-performance HVAC systems, a COP value of 3 is used.

Electricity consumption of HVAC = Heating demands/ COP = 8,973 kWh/y / 3 = 2,991 kWh/y

Thus, the total electricity consumption of the HVAC system is **4,695 kWh/y.**

To sum up, in Thessaloniki demo site, a high-performance HVAC system is used to cover the 8,973 kWh/y heating demands and 8,520 kWh/y cooling demands which lead to an electricity consumption of 4,695 kWh/y and 93,900 kWh during the lifetime of the project (Table 12).

3.1.3.4 MiniStor System

The operation of MiniStor and the specific energy needs of each site determine the inputs and the outputs of energy balances. Inputs include the amount of energy used by MiniStor, the type of energy source, the source's efficiency, and the heating needs that are not capable of being covered by MiniStor. The output includes the total heating demand of the site and the electricity produced by MiniStor.

Calculations

With the integration of MiniStor System, based on simulated data from D3.1 and D6.7 the required electricity consumption of the HVAC is reduced as follows:

In Thessaloniki, MiniStor can cover at least 5,915 kWh/y of the heating and 3,199 kWh/y of the cooling demand. Thus, following the same logic as in baseline approach the remaining load will be covered by PV field (PVGIS) as follows:

    o   Electricity consumption for cooling

For high-performance HVAC systems, cooling efficiency, EER equals to 5.

Electricity consumption of HVAC = Cooling demands/ EER = 5,321 kWh/y / 5 = **1,064 kWh/y**

    o   Electricity consumption for heating

For high-performance HVAC systems, a COP value of 3 is used.

Electricity consumption of HVAC = Heating demands/ COP = 3,058 kWh/y / 3 = **1,019 kWh/y**

Thus, the total electricity consumption of the HVAC system is 2,083 kWh/y.

On this value the electricity for MiniStor operation is added. However, the electricity produced by RES (PVGIS), which is equal to 4,220 kWh/y in Thessaloniki, covers the total amount of MiniStor electricity demand (1,955 kwh/y). The extra energy is directed into the electrical grid. According to Table 12, the energy demand of MiniStor is totally covered in both replication sites, Larnaca and Rome.

3.1.4 End of Life phase

Concerning the end-of-life stage, there were different types of treatment based on the materials. Since solid TCMs are inert and non-solvable, it is considered that they will be disposed of in landfills. Chocontá Bernal et al, 2021 considered that the phase change materials are incinerated while wastewater treatment is indicated for the heat transfer fluid. Recycling is applied for all metals used, namely steel, aluminum and copper, such as in studies of Berger et al (2022) and Bonamente and Aquino 2020. Regarding the heat transfer fluid, it was assumed that it would be treated in a wastewater treatment plant. The remaining components are disposed of in landfills (Lalau et al, 2020). Disposal was not considered for the lubricating oil and the battery (as secondary data were not available). The end-of-life phase of each material has already been included in the processes of each component. **¡Error! No se encuentra el origen de la referencia.** and **¡Error! No se encuentra el origen de la referencia.** provide the manufacturer data imported to the processes of disposal.

3.2 Environmental assessment

3.2.1 Environmental impact of MiniStor System infrastructure

The sub-systems considered in MiniStor system are very different and thus separately evaluated. The environmental assessment was conducted for each infrastructure of each component.

Annex II Table 2 presents the major impacts in climate change (kg CO_{2eq}), in primary energy or else the fossil and nuclear energy use (MJ deprived) and in the water scarcity (m^3 $world_{eq}$) during the manufacturing stage of a solar assisted unit in case of a 1.55 m^2 PVT and a 2.37 m^2 FPC. Moreover, illustrates the total impact assessment of all the MiniStor System infrastructure on the three major midpoint impact categories whereas

Annex II Table 3 to

Annex II Table 14 present the impact of these three categories but separately and in detail for each component of the MiniStor system.

Table 13. Summary of environmental assessment during manufacturing stage for MiniStor System infrastructure

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
	kg CO_{2eq}	MJ deprived	m^3 world eq
Total	1.98E+04	2.77E+05	1.72E+04
Solar area	3.67E+03	4.50E+04	1.78E+03
Hot water tank with heater	1.14E+02	1.67E+03	5.29E+01
Remaining Infrastructure	2.59E+03	3.25E+04	1.05E+03
TCM reactor	8.01E+02	1.19E+04	3.72E+02
Heat transfer fluid	2.11E+02	5.23E+03	2.33E+02
Ammonia Compressor	8.25E+02	1.09E+04	3.78E+02
Lubricating oil Separator	5.77E-01	7.47E+00	2.51E-01
Lubricating oil	7.85E-01	4.60E+01	2.56E-01
Ammonia Condenser Infrastructure	3.46E+01	4.70E+02	1.28E+01
Ammonia Evaporator Infrastructure	3.60E+01	4.74E+02	1.27E+01
Liquid Ammonia tank	1.32E+02	1.85E+03	4.36E+01
Heat Pump	2.05E+02	1.81E+03	7.12E+01
Hot PCM	4.13E+02	5.54E+03	1.16E+02
Cold PCM	1.21E+03	1.22E+04	2.35E+02
Hot DHW	5.70E+02	8.19E+03	1.74E+02
Pumps	2.09E+01	2.72E+02	1.09E+01
Control unit	4.83E+02	7.08E+03	3.52E+02
Metallic Container	5.42E+03	7.49E+04	2.00E+03
BESS_ Hybrid solar inverter	4.00E+02	6.12E+03	1.42E+02
BESS_Li-ion Battery	2.69E+03	5.07E+04	1.02E+04

Figure 13 illustrates the percentage contribution of each component of the MiniStor to the eighteen impact categories whereas Figure 14 presents the three out of eighteen investigated impact categories that have been set under investigation in this study. Major contributors to climate change, in descending order of impact, are the MiniStor metallic container (27%), the solar area (18%) and the Li-on battery of BESS (14%) (Figure 14). The MiniStor metallic container is contributing the most to long-term climate change impact (5.42E+03 kg CO_2eq), indicating that the container contributes to cumulative GHG emissions over its lifecycle. Regarding fossil and nuclear energy use, the metallic container following by solar area appear with the highest contribution (4.50E+04 MJ and 3.67 MJ), suggesting that a significant amount of energy from non-renewable sources is consumed during the production of the containers and solar components. Moreover, the solar area contributes moderately to photochemical oxidant formation (2.54E+01 kg NMVOCeq), which may be related to emissions from the production processes of solar components. Volatile organic compounds (VOCs) and other pollutants could be emitted during the manufacturing of solar panels and metal supports, contributing to this impact category. It is noteworthy to mention that the solar area contributes the most in each impact midpoint category except for the mineral resource use, the human toxicity cancer and the freshwater eutrophication, in comparison with the remaining components. Generally, it is noteworthy to mention that in climate change the solar assisted unit, weighing almost 1 ton, is responsible for 32% of the overall impact of the system. In addition, the

840 kg MiniStor metallic container shows significant contribution in climate change and fossil and nuclear energy use categories, indicating that its production process likely involves substantial energy consumption, possibly from non-renewable sources, and high greenhouse gas (GHG) emissions. This is due to the materials (e.g., metals like steel and aluminum) that require a lot of energy to produce and process. Furthermore, the metallic container has a relatively substantial impact on human toxicity (cancer) with (55% contribution since the MiniStor container weights 721 kg). This suggests that the manufacturing processes, for instance mining and smelting of metals and possibly the end-of-life management of the metallic container involve processes or materials that have significant carcinogenic risks to humans.

In Figure 15, the three major contributors in climate change are presented separately. Regarding the solar area and considering every midpoint impact category, the PVT is responsible almost for 66% of 680 kg of solar area, with the remaining 34% attributed to the FPC (Figure 16). Further analysis of the components that comprise the solar assisted unit revealed that the PVTs and metallic structures are the primary contributors to all three environmental impact categories (Figure 17). The auxiliary heater has the least environmental impact. The examination of the materials involved in the metallic container manufacturing and their environmental impacts provides that the chromium steel and metalworking dominate the environmental footprint, particularly affecting climate change and water use. This highlights the energy-intensive and resource-demanding nature of stainless-steel production (Figure 18). Regarding the BESS components, both hybrid solar inverter and Li-ion battery have high impacts across the following categories: climate change, fossil and nuclear energy use, mineral resource use and water scarcity (Figure 19). Li-ion batteries require a significant amount of energy to manufacture and contain minerals such as lithium, cobalt, and nickel, which are not only energy-intensive to extract but also have a negative environmental impact owing to mining techniques. In addition to this, Li-ion batteries have 59% impact on water scarcity, possibly due to the water use in their manufacturing processes (Yuan et al., 2021). The components with the lower contribution to all the midpoint categories are the pumps, the lubrication oil and the lubricating oil separator with less 0.1% contribution to climate change, fossil fuel and water scarcity.
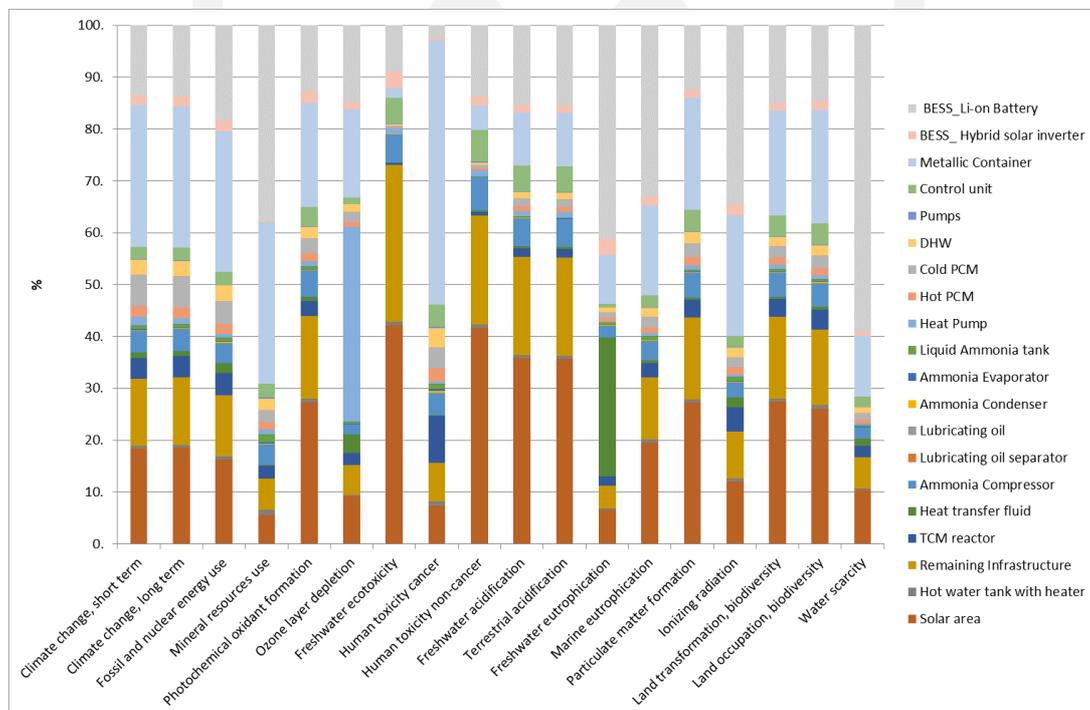
Figure 13. Percentage of environmental midpoint impacts from all the components of MiniStor System
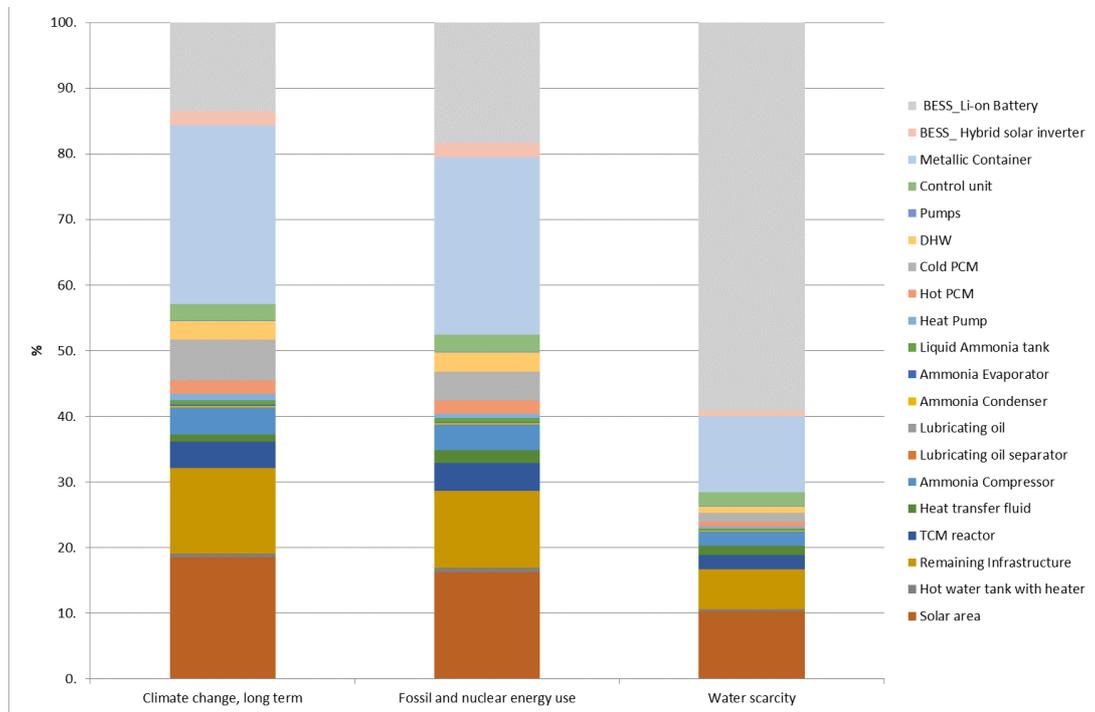
Figure 14. Contribution (%) of all the components of MiniStor System to three investigated categories; climate change, fossil and nuclear energy use and water scarcity
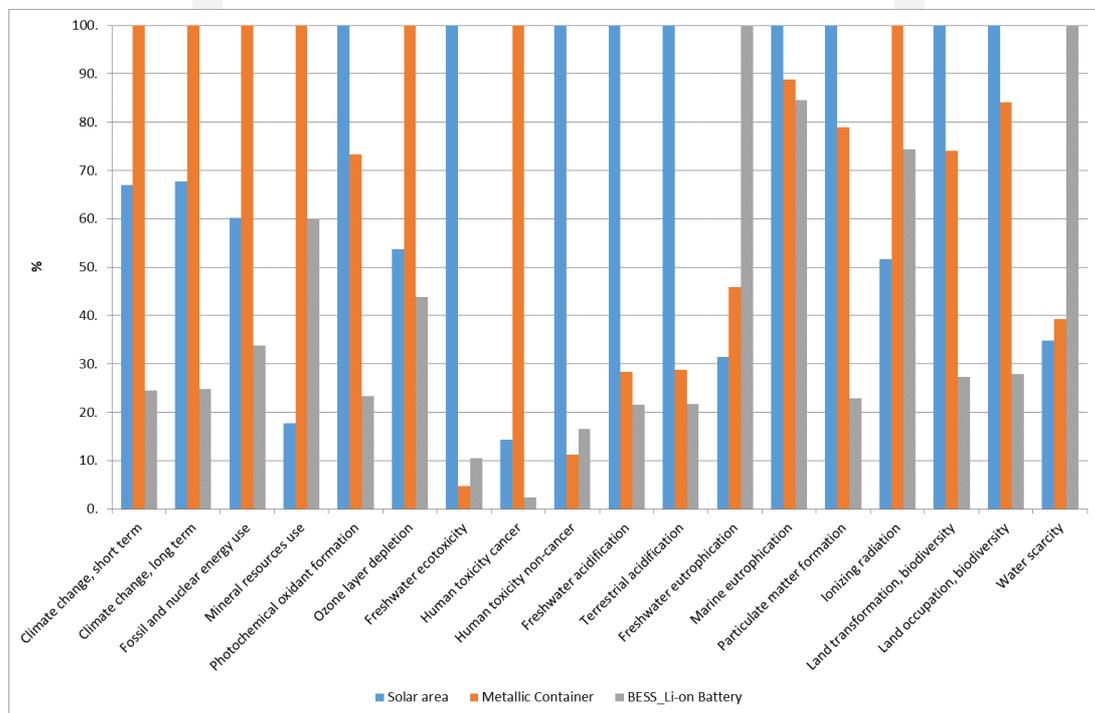
Figure 15. Contribution of environmental midpoint impacts from the major contributors (solar area, metallic container and Li-on battery of BESS) of MiniStor system.
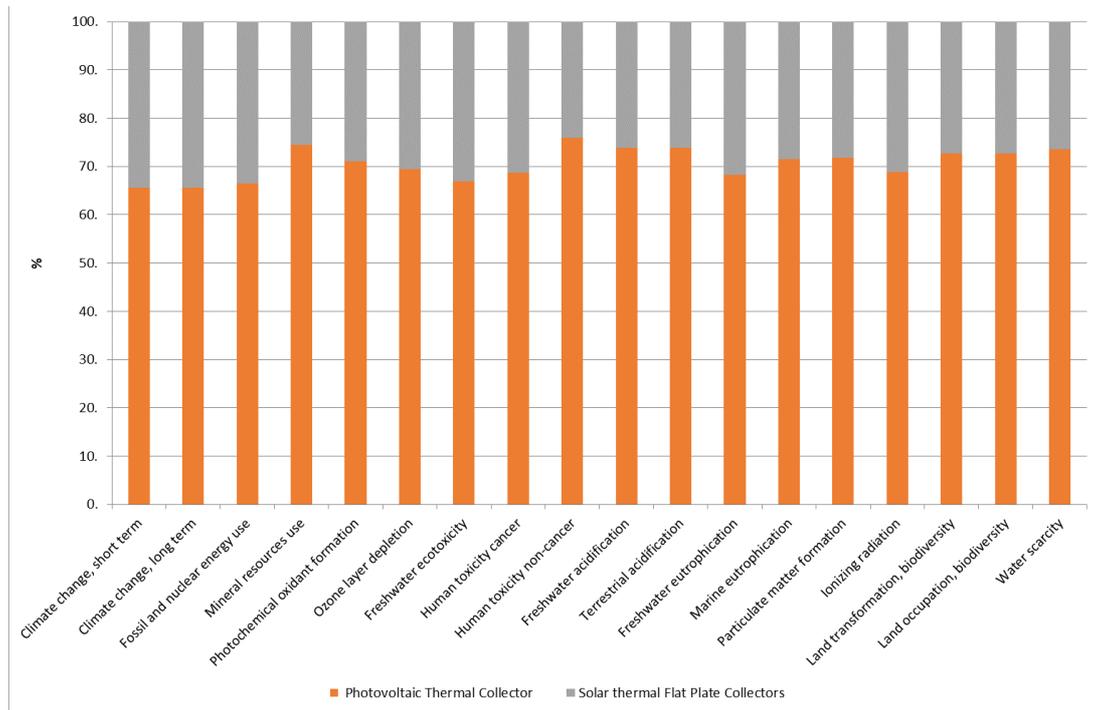
Figure 16. Contribution (%) of solar area components of Thessaloniki to midpoint impact categories.
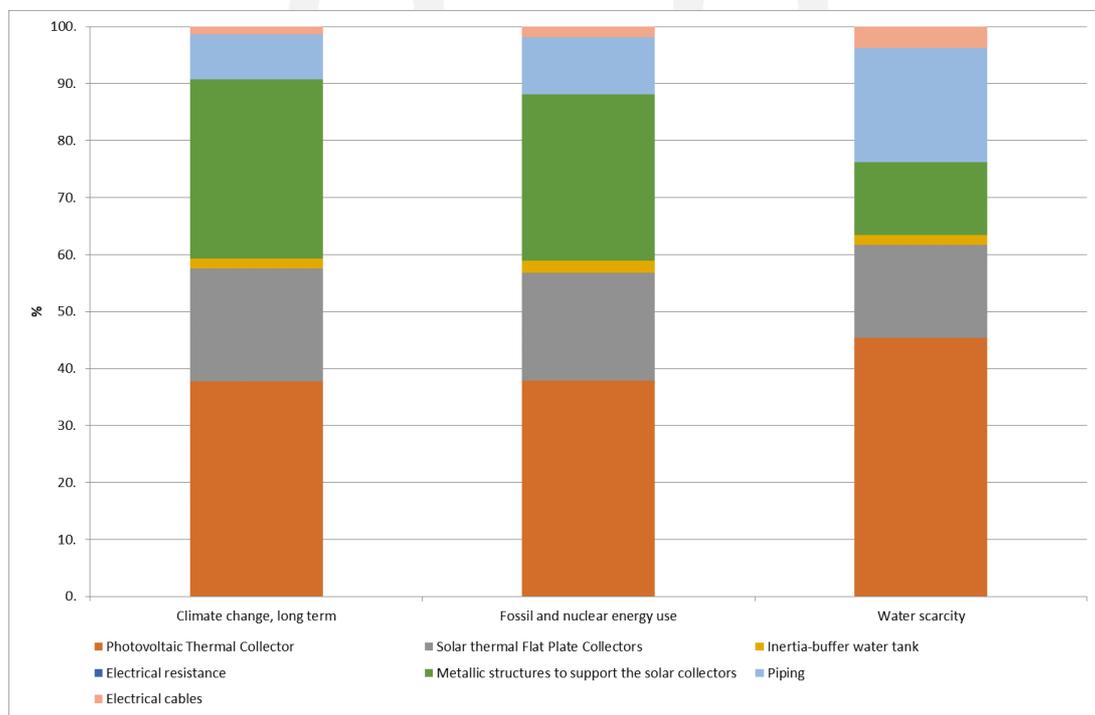
Figure 17. Contribution (%) of each component of solar assisted unit to climate change, to fossil and nuclear energy use and to water scarcity
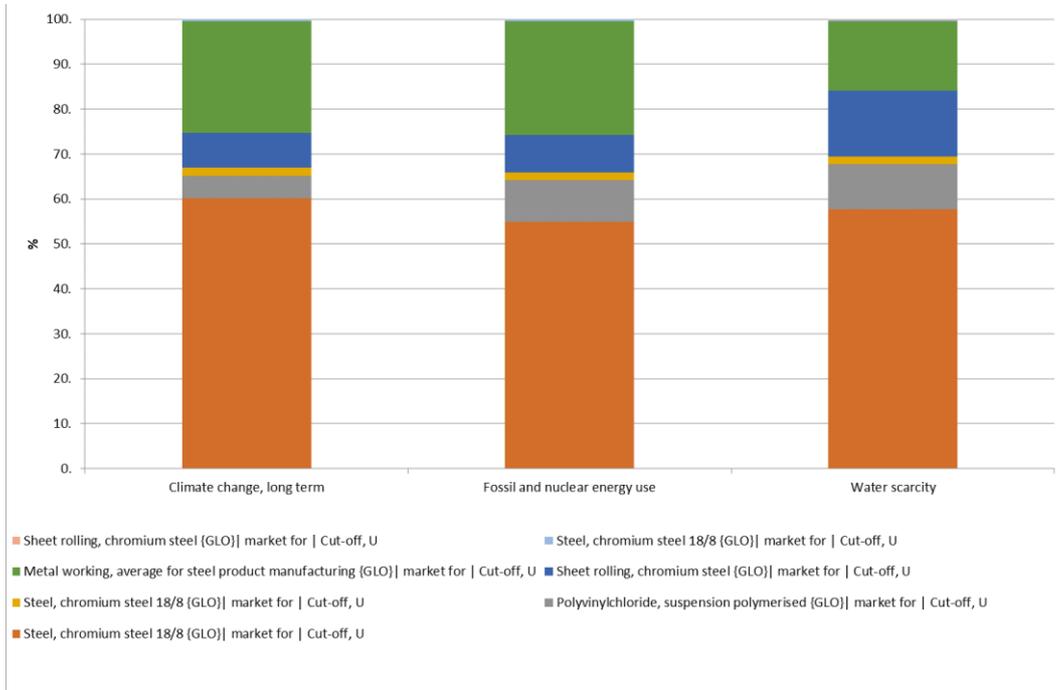
Figure 18. Contribution (%) of each component of metallic container to climate change, to fossil and nuclear energy use and to water scarcity
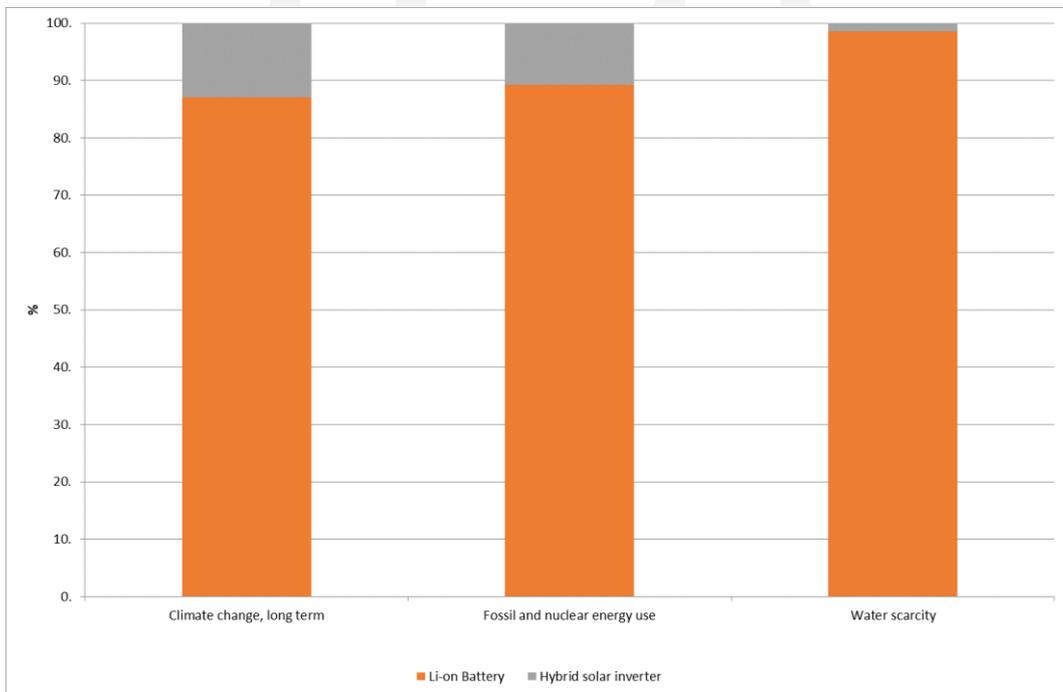
Figure 19. Proportion of the battery energy storage system (BESS) to the impact of climate change, to fossil and nuclear energy use and water scarcity
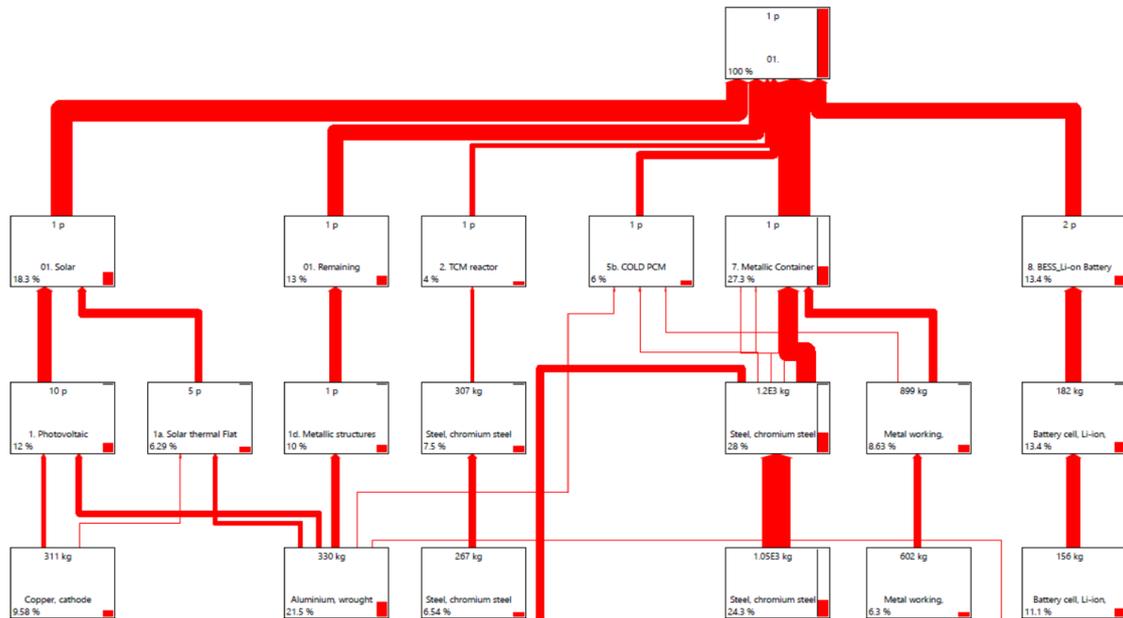
Figure 20. LCA network output for assessing environmentally the infrastructure of each component involved in MiniStor System in kg CO_{2eq} (with cut-off rules)
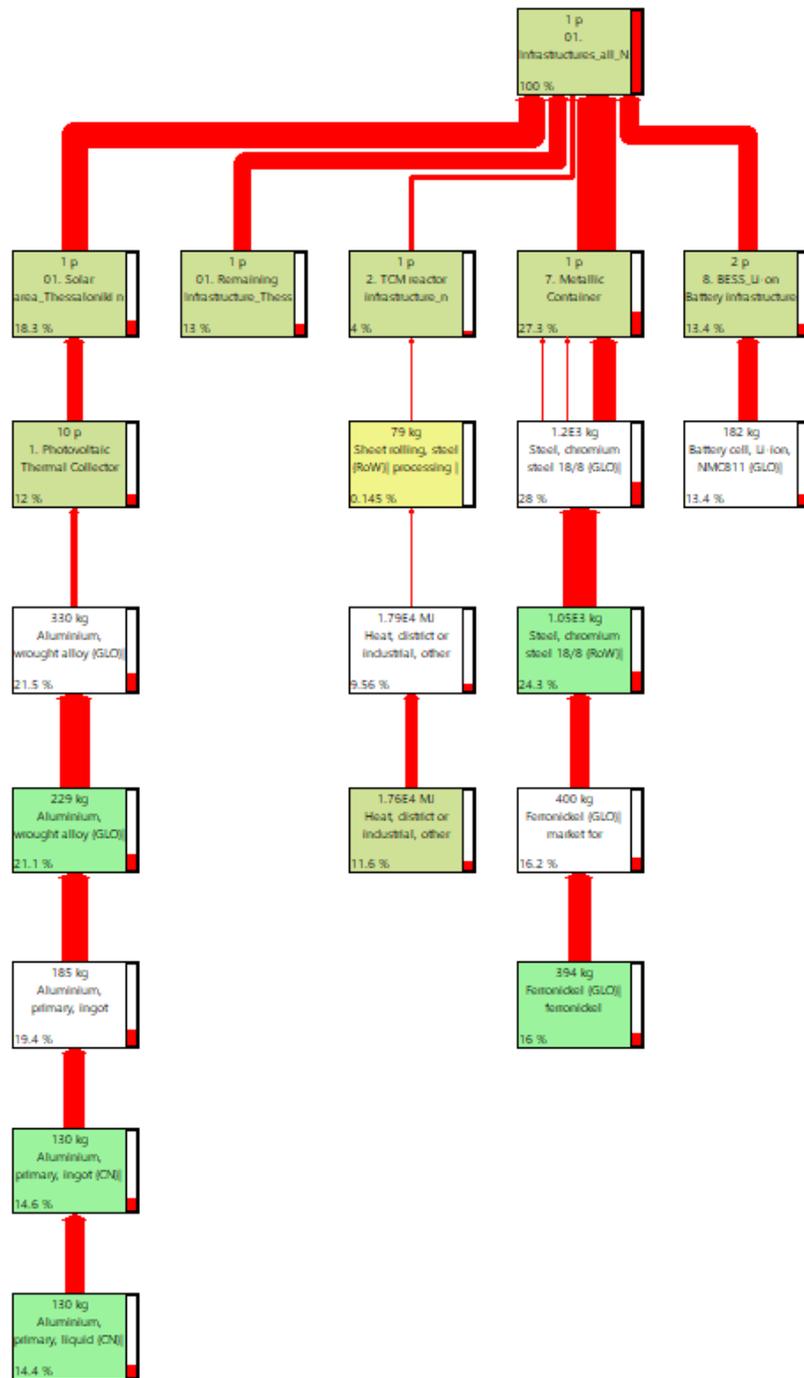
Figure 21. LCA network output for assessing environmentally the infrastructure of each component involved in MiniStor System in %

3.2.2   Environmental impact of MiniStor System during operation

MiniStor is operated using renewable energy acquired from the solar field. In case the energy is not adequate for the MiniStor operation then the electricity mix is used. In Thessaloniki the renewable energy can both be used for MiniStor operation and to be fed into electricity network. The data are obtained from Ecoinvent database following the consistency of data origin. Regarding Thessaloniki

demo site, taking into consideration both the operation and the infrastructure of the whole MiniStor System the environmental assessment on climate change and primary energy (*fossil and nuclear energy use*) are estimated at 1.71E+04 kg CO$_{2eq}$ and 2.34E+05 MJ. The LCA outcomes regarding Thessaloniki demo site reveal that the infrastructure burdens the total impact on all the midpoint impact categories as the MiniStor operation is covered in total by RES (Figure 22).
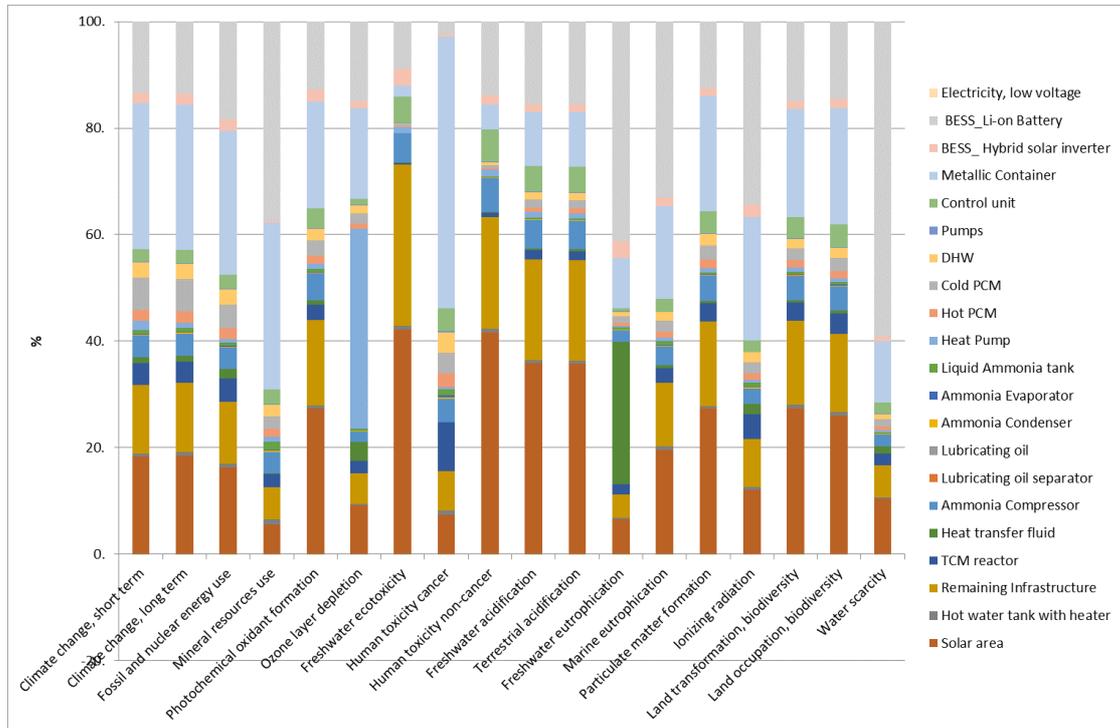
Figure 22. Environmental assessment of the operation and infrastructure of MiniStor system in eighteen impact categories based on IMPACT World+ Midpoint V1.01 method in Thessaloniki demo site.

Comparing the total impact of the MiniStor System on climate change (kg CO$_{2eq}$), including the infrastructure and operation impact, with the baseline which encompasses the operation impact of the HVAC existing system in Thessaloniki demo site, revealed a significantly better environmental performance (Figure 23 - Figure 25). This comparison indicates a 4% benefit in case of use of MiniStor system over the baseline system. This benefit reflects the climate change impacts mitigation by the integration of the MiniStor system. As already mentioned, the operation impact of MiniStor System on climate change (-2.74E+03 kg CO$_{2eq}$) is negative as the electricity demand of MiniStor is totally covered by the PV field and moreover the extra energy is added to the grid. The high values in water scarcity in MiniStor system reflect the high burden of infrastructure with 60% attributing to Li-ion Battery. Furthermore, the environmental assessment of MiniStor system for the major categories of climate change, the fossil and nuclear energy use and the water scarcity in eight replication sites Paris (France), Krakow (Poland), Berlin and Hamburg (Germany), Bergen (Norway), Larnaca (Cyprus), Athens (Greece) and Rome (Italy) included in Annex II Figure 1 to Annex II Figure 8. Alongside Thessaloniki, Larnaca and Rome benefited by 23 and 25%, respectively, from using the MiniStor system. This is explained by the high solar radiation of these regions and consequently of high electricity production by RES.
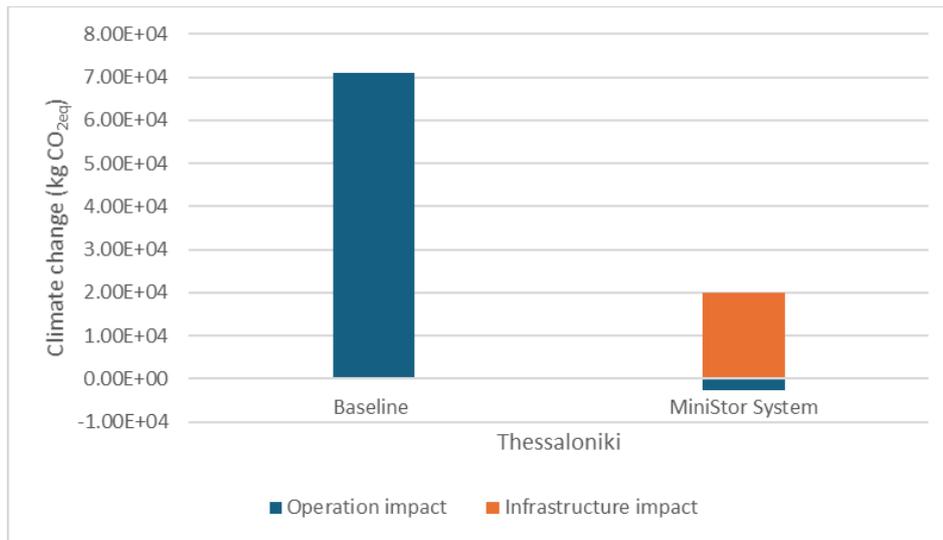
Figure 23. Comparison of MiniStor system climate change (kg CO_{2eq}) with Baseline according to IMPACT World+ Midpoint V1.01 method in Thessaloniki demo site during the lifetime
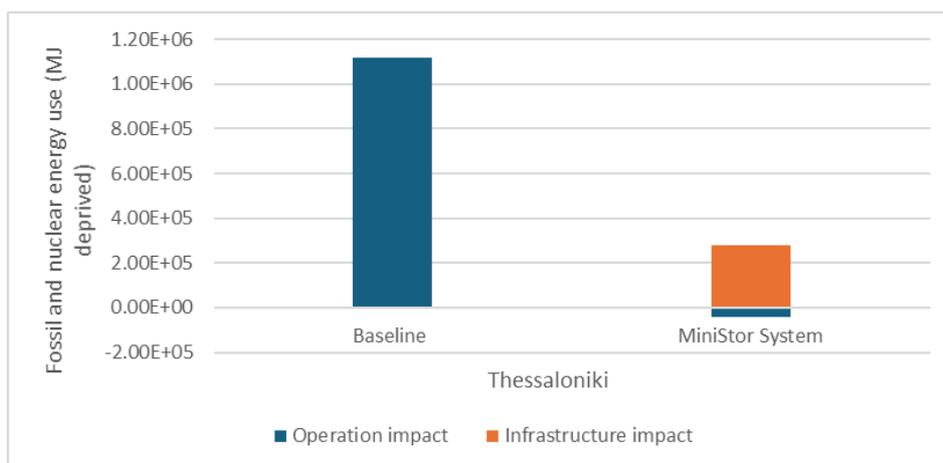
Figure 24. Comparison of MiniStor system fossil and nuclear use (MJ deprived) with Baseline according to IMPACT World+ Midpoint V1.01 method in Thessaloniki demo site during the lifetime

A comprehensive analysis of total impact of climate change (kg CO_{2eq}) comparing all the replication sites and the demo site of Thessaloniki, in case of Baseline to the MiniStor System implementation, revealed that MiniStor system leads to decrease in overall impact (operation and infrastructure impact) in the majority of the sites (Figure 25). On the contrary, in Paris, Berlin, and Hamburg the total impact of climate change in MiniStor case is higher (296%, 7% and 10%), however this is owning to the infrastructure burden while MiniStor's operation impact is decreased by 42%, 17% and 24%, respectively. A significant role in operation phase plays the electricity mix. As it has already been mentioned in section 3.1.3.1 for each replication site the electricity mix is based on site location. The climate change impact of the electricity mix of the three above-mentioned sites ranges from 0.3 to 0.5 kg CO_{2eq}/ kWh. Annex II Figure 9 presents separately the operation and the infrastructure impact of MiniStor system. Furthermore in Annex II Figure 10 and Annex II Figure 11 are illustrated the comparison of total impact of MiniStor system regarding the fossil and nuclear use (MJ deprived) with baseline according to IMPACT World+ Midpoint V1.01 method and water scarcity (m³ world eq), respectively, for the demo and replications sites.
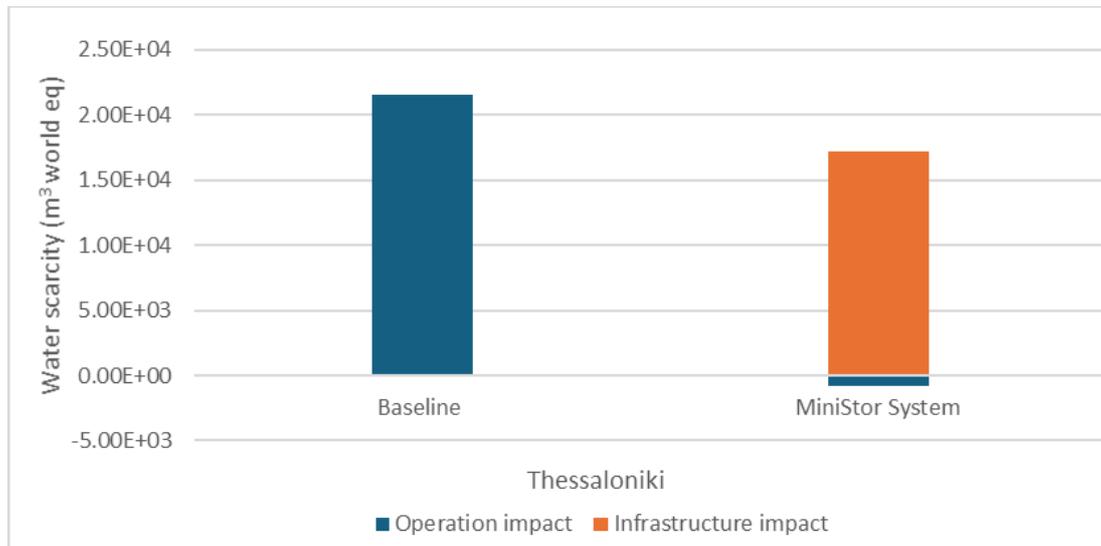
Figure 25. Comparison of MiniStor system water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Thessaloniki demo site during the lifetime
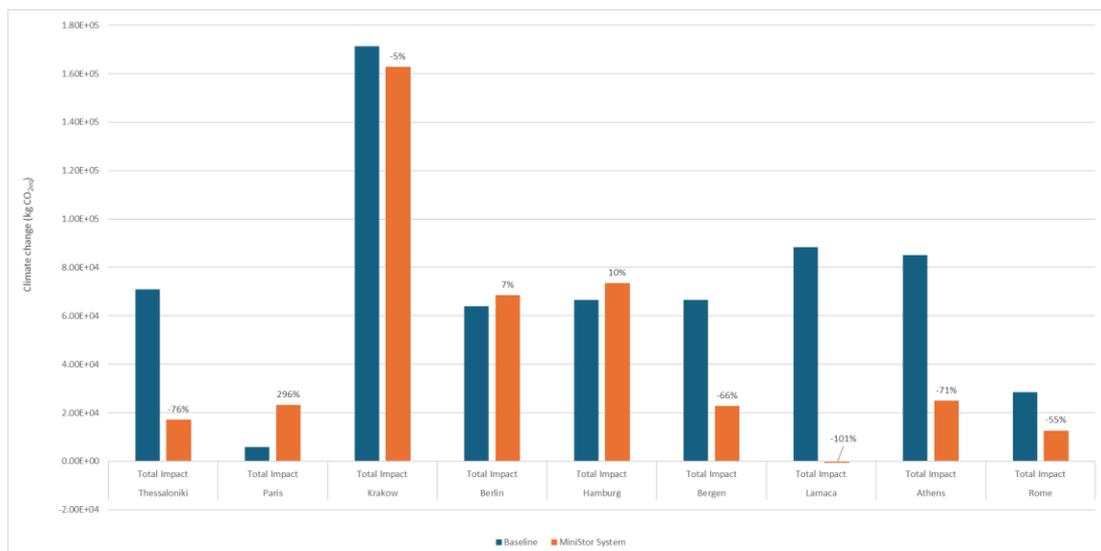
Figure 26. Comparison of the total impact of climate change (kg CO_{2eq}), operation and infrastructure stage, in case of the baseline scenario and in case of MiniStor system for the demo site and replication sites during the lifetime

3.3 Sensitivity Analysis – Scenarios

To perform the sensitivity study, one parameter is modified at a time while the others remain constant at their reference value. The estimated environmental impact indicators vary because of parameter variation. The purpose of the sensitivity analysis was to assess how varying the types of heating system (conventional), in case of integration of MiniStor system or not, will affect the environmental impact categories.

Comparison of conventional types of heating systems to MiniStor – Thessaloniki demo site

Three scenarios were evaluated to compare MiniStor's environmental in the Thessaloniki demo site:

- **Scenario 1**: An electrically driven heat pump with a COP of 3 and an EER of 5 is used for both heating and cooling. The heat pump serves as the primary source of heating and cooling. If MiniStor's stored heat is insufficient, the heat pump supplies the additional energy required. Any excess electricity produced by the PVT system is returned to the local grid.
- **Scenario 2**: A light fuel oil boiler with an average thermal efficiency of 80% and an electrically driven heat pump are used for heating and cooling. The boiler provides heating, while the heat pump handles cooling. If the MiniStor's stored heat is insufficient for heating, the boiler compensates for the shortfall. Likewise, if MiniStor cannot fully meet cooling demands, the heat pump supplies the required energy. Any surplus electricity generated by the PVT system is fed back into the local grid.
- **Scenario 3**: A natural gas boiler with an average thermal efficiency of 90% provides heating, while an electrically driven heat pump handles cooling. If the MiniStor's stored heat is insufficient for heating, the boiler supplies additional energy. Similarly, the heat pump covers any unmet cooling demands. Any excess electricity generated by the PVT system is fed into the local grid.

Table 14 presents the Ecoinvent process that is used in each scenario. For every scenario, the baseline and the MiniStor system were compared. Furthermore, the under-investigation scenario 1 is the scenario studied in § 3.2.2.

Table 14. Selection of the alternative scenarios on Ecoinvent database

Scenario	Process	Ecoinvent process
1	Heat production using heat pump	Electricity, low voltage
2	Heat production using oil and specifically a light fuel oil boiler	Heat, central or small-scale, other than natural gas {Europe without Switzerland}, heat production, light fuel oil, at boiler 10kW, non-modulating | Cut-off, U
3	Heat production using natural gas boiler	Heat, central or small-scale, natural gas {RER}| market group for | Cut-off, U

Figure 27 illustrates a comparison of the total climate change impact (kg CO_{2eq}) before and after the MiniStor installation for heating with an oil boiler (Scenario 2). It is clear that the infrastructure is the major contributor. As far as it concerns the operation impact, after MiniStor system installation the climate change impact decreased 93% (7.36E+03 kg CO_{2eq}) while the total impact decreased 73%, (an order of magnitude larger than that of baseline (1.01E+05 kg CO_{2eq} versus 2.02E+04 kg CO_{2eq}). Regarding the eight replication sites and their environmental impact with and without MiniStor system installation are depicted from Annex II Figure 12 to Annex II Figure 19. A comparison between the outcomes regarding the total impact of climate change (kg CO_{2eq}) before and after the MiniStor installation in demo site of Thessaloniki and the eight-replication site is illustrated in Figure 30. It is essential to mention that installing the MiniStor system decreases the environmental impact due to lower CO_{2eq} emissions than those of the baseline. In terms of the total impact, the decreases vary from -90% (Larnaca) to -9% (Krakow) comparing the demo and replication sites. In terms of operation phase the range is larger than that of total and the reduction ranges between -109% (Larnaca) to -18% (Krakow). Similar comparisons considering fossil and nuclear use (MJ deprived) and water scarcity (m³ world eq) are presented in Annex II Figure 20 and Annex II Figure 21.
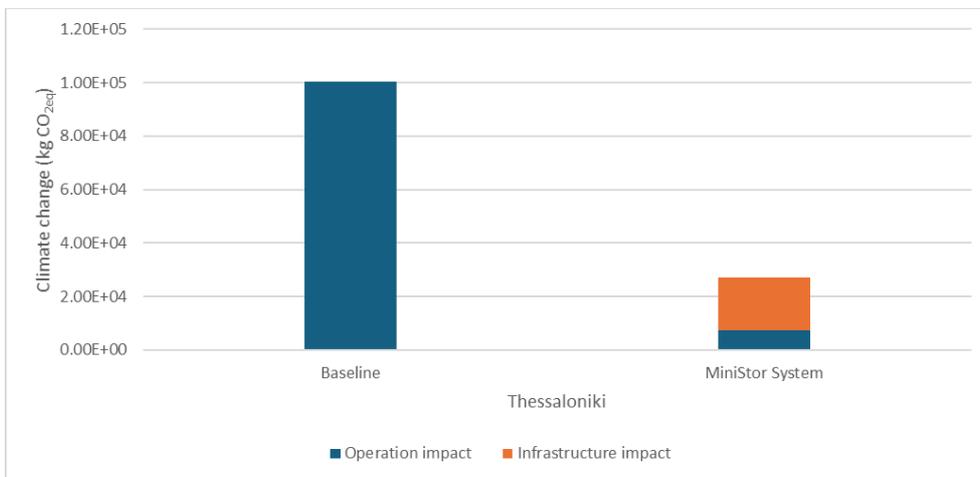
Figure 27. Comparison of MiniStor system's impact on climate change (kg CO2eq) with Baseline in Thessaloniki, over its lifetime under Scenario 2
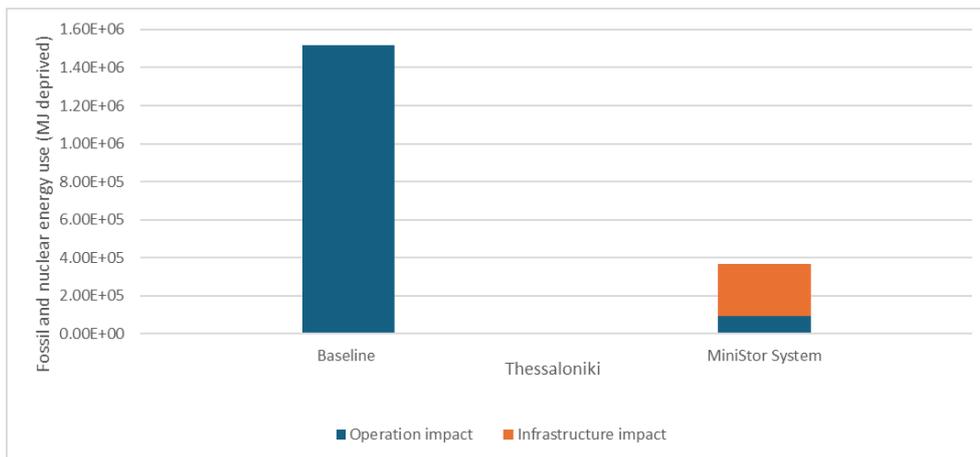
Figure 28. Comparison of MiniStor system's impact on fossil and nuclear energy use (MJ derived) with Baseline in Thessaloniki over its lifetime under Scenario 2

Figure 29. Comparison of MiniStor system water scarcity (m³ world eq) with Baseline in Thessaloniki over its lifetime under Scenario 2

Figure 30. Comparison of the total impact of climate change (kg CO_{2eq}), operation and infrastructure stage, in case of the baseline and MiniStor system for the demo site and replication sites during the lifetime under Scenario 2

For Scenario 3, Figure 31 illustrates a comparison of the total climate change impact (kg CO_2eq) before and after the MiniStor installation, specifically for heating with a natural gas boiler. It is clearly evident that the MiniStor system installation improves the environmental impact likewise to the 2nd scenario. As far as it concerns the operation impact, after MiniStor system installation the climate change impact decreased 102% while the total impact decreased 75%, (7.55E+04 kg CO_{2eq} versus 1.87E+04 kg CO_{2eq}). Regarding the eight replication sites and their environmental impact with and without MiniStor system installation is depicted in Annex II Figure 22 to Annex II Figure 29. A comparison between the outcomes regarding the total impact of climate change (kg CO_{2eq}) before and after the MiniStor installation in Thessaloniki demo site and the eight-replication site is illustrated in Figure 34. It is significant to note that the MiniStor system installation decreases the environmental impact due to lower CO_2 emissions than those of the baseline. In terms of the total impact, the decreases vary from -107 % (Larnaca) to -1% (Krakow) comparing the demo site and all the replication sites. In terms of operation phase the range is larger than that of total and the reduction ranges between -132% (Larnaca) to -15% (Krakow). Similar comparisons considering fossil and nuclear use (MJ deprived) and water scarcity (m^3 world eq) are presented in Annex II Figure 30 and Annex II Figure 31.
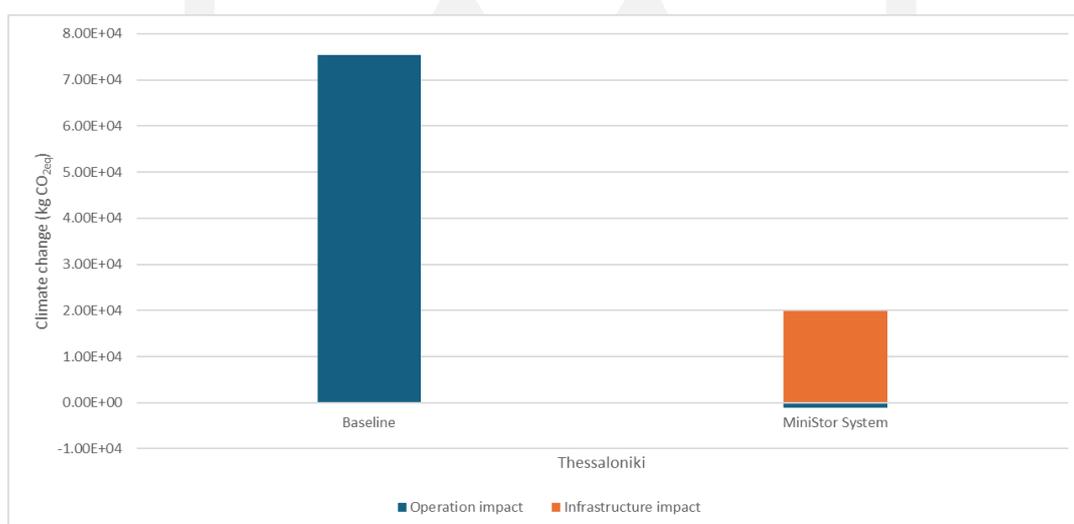
Figure 31. Comparison of MiniStor system climate change (kg CO_{2eq}) with Baseline in Thessaloniki over its lifetime under Scenario 2
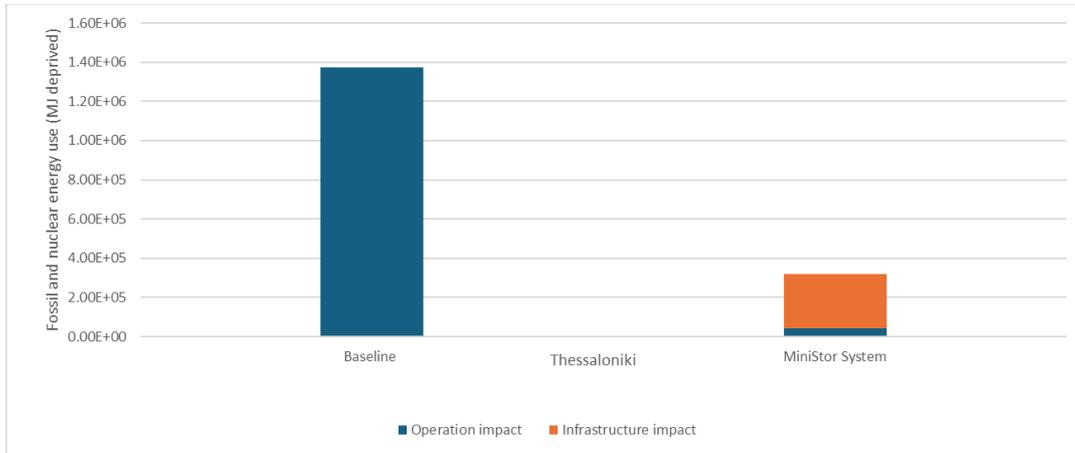
Figure 32. Comparison of MiniStor system fossil and nuclear use (MJ deprived) with Baseline in Thessaloniki over its lifetime under Scenario 3
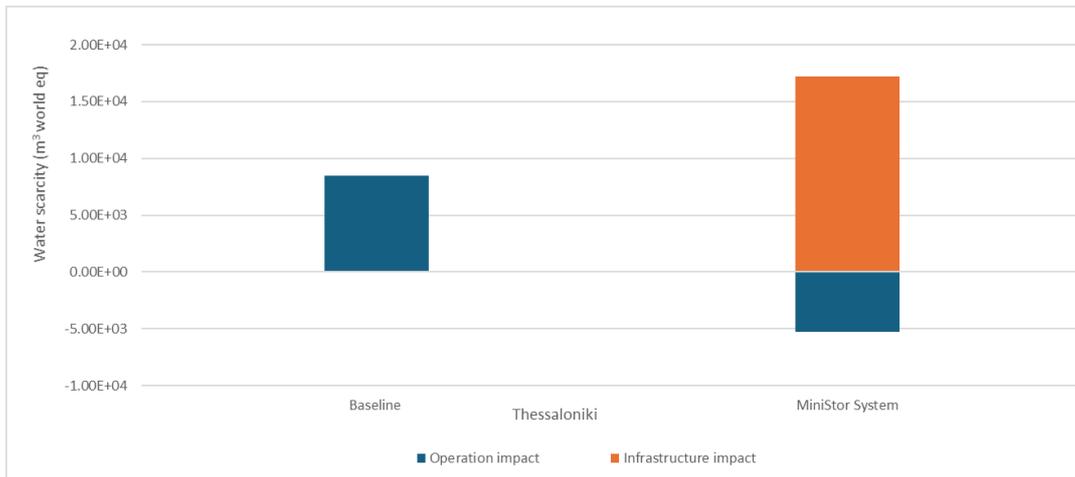
Figure 33. Comparison of MiniStor system water scarcity (m^3 world eq) with Baseline in Thessaloniki over its lifetime under Scenario 3

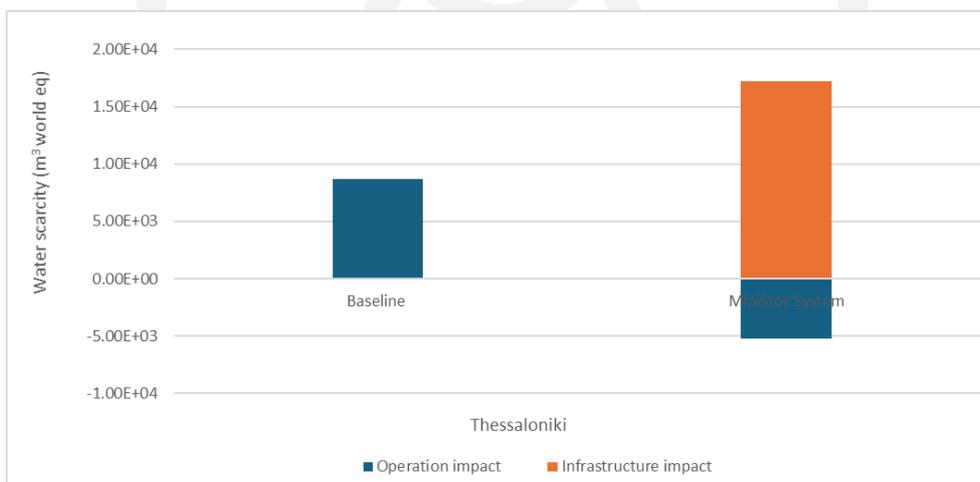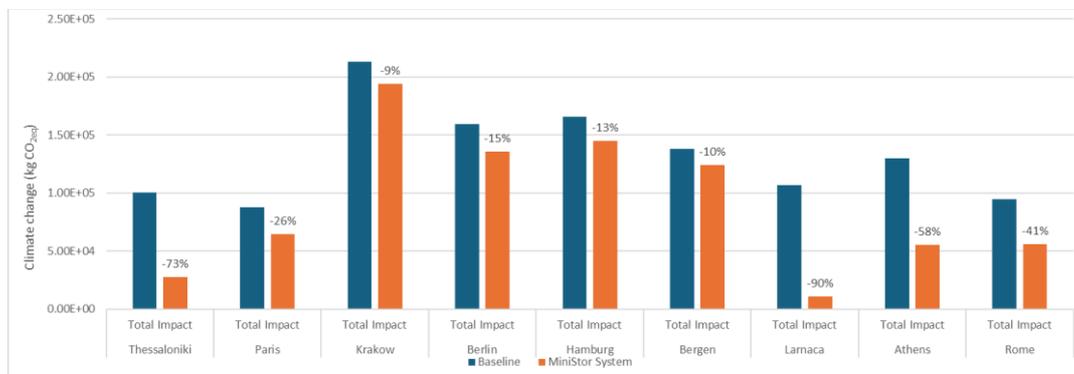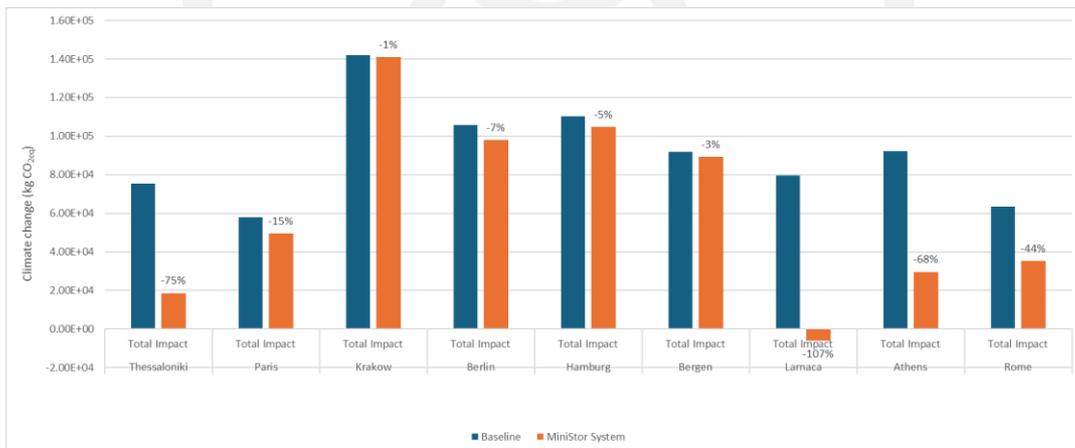Figure 34. Comparison of the total impact of climate change (kg CO_{2eq}), operation and infrastructure stage, in case of the baseline and MiniStor system for the demo site and replication sites during the lifetime under Scenario 3

Finally, a comparison among the three under investigation scenarios of the total impact of climate change in the baseline case and in case of the MiniStor system integration is presented in Figure 35. The results indicate that the MiniStor system is beneficial, consistently reducing environmental impact regardless of the heating method, with an average reduction of 75%. However, Scenario 2 is deemed "unprofitable" despite MiniStor installation, as its CO_2 emissions remain 30% higher than those of the other two scenarios.
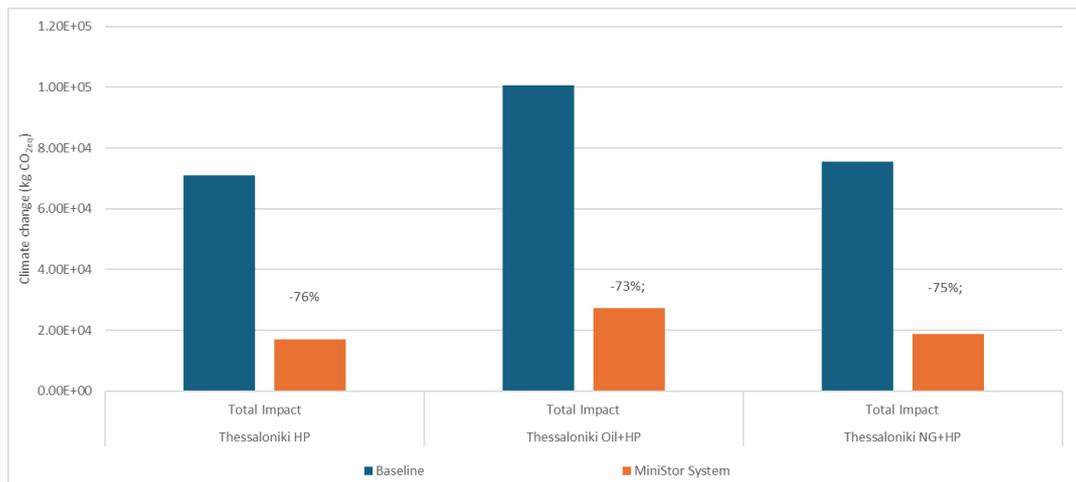
Figure 35. Comparison of the total impact of climate change (kg CO_{2eq}) of the MiniStor system in Thessaloniki between Baseline and the three Scenarios

3.4   Social perspectives on thermal storage system

The social aspect of the TES system has been investigated through relevant studies. Borri et al. (2024) reported the social effects of a novel TES developed employing selected water sorbents to enhance the use of renewable energy in domestic heating. They emphasized that the social impact of TES systems is often neglected, posing a barrier to market acceptance. Their study showed a medium-high social effect with improvement's potential, especially in the manufacturing and end of life phases. Local communities, value chain participants, customers, employees, and society are all encompassed in the stakeholder groups. Stronger interaction with local communities is suggested which is based on qualitative data from businesses involved at different life-cycle stages. Additionally, even if customers are positively inclined to the novel system there is a demand for more transparent communication. The impact on workers could be improved by enhancing social benefits and security. Additionally, societal commitment to sustainability is relatively low, indicating an opportunity for companies to invest more in technology deployment, research, and innovation. For low carbon buildings a TES can be embodied to a building to improve its energy efficiency (EECA, 2019). The social acceptance of low carbon buildings (LCB) was assessed through social surveys (questionnaires) taking into account community, social, and market perspectives (Alam et al., 2020). They revealed that 59.72% of the 70 respondents believed LCBs could reduce greenhouse gas emissions, and over 53% were willing to upgrade their homes to LCBs. However, 70% were reluctant to hire a consultant due to concerns about the costs associated with LCBs. Sibilla and Kurul (2023) examined the shift towards renewable, decentralized, and citizen-centered energy systems. They highlighted the role of energy storage systems (ESSs) to grid stability enhancement and local energy autonomy. They mentioned the importance of social perspectives in ESSs at larger scales, focusing on three key pillars: geographical and institutional scales, social aspects of flexibility, and co-creation strategies for ESS deployment. This study emphasizes the importance of citizen involvement and flexible digital platforms to optimize the advantages of shared renewable energy, suggesting that solutions should be customized to meet the needs of stakeholders. Even though TES technologies are feasible and competitive, due to social, cultural,

and legal barriers are difficult to accept. Simo-Solsona et al, 2021 examined (questionnaires on professionals) these challenges in Spain, revealing that the 2008 economic crisis and the poor condition of existing buildings limit the implementation of retrofitting measures, including TES.

Additionally, a lack of professional expertise, limited dissemination of best practices, and concerns over long-term performance impede the adoption of TES technologies in the region. Concerning BESS, even though there is extensive research on environmental impacts, social acceptance is examined in limited number of studies. In most s-LCA studies, qualitative indicators are in favor than quantitative. The selection of the social indicators for s-LCA might be difficult and possibly biased due to the lack of a standardized methodology. Cellura et al. 2024 evaluate studies with the aim of promoting sustainable decision-making solutions in all phases of life cycle. The most common stakeholder categories in studies considered the local communities and the entire society while the most common impact category is worker conditions, including health and safety, freedom of collective bargaining, fair wages, and child labor. Lithium-ion battery manufacture is the most widely evaluated scenario. Cellura et al. 2024 concluded that more research is necessary to define the social impacts of batteries, including objective analyses that quantify impacts across life cycle phases and allow for comparisons between different scenarios with high variability.

To sum up, the social impact of TES systems reveals significant barriers to wider adoption, particularly in areas such as manufacturing, end of life stages, and professional expertise. Although TES and low-carbon buildings are thought to be beneficial, the cost and the long-term performance considered barriers to acceptance. Two key factors essential to decentralized energy systems are the citizen's participation in decision machining processes and flexible digital platforms. Finally, more research is required to better quantify the social impact of ESS throughout their life cycle.

3.5 Validation of LCA outcomes

To validate the obtained outcomes into perspective, similar cases focused on climate change of different thermal energy storage systems selected from literature. Herrando et al.'s (2022) studied a similar system to MiniStor and performed a life cycle assessment on a building energy system that integrates cooling, heating, domestic hot water, and electricity production. Their system can reduce greenhouse gas impacts (82,400 kg CO_{2eq}) by 30% over conventional systems. Zsembinszki et al. (2021) analyzed an advanced hybrid system with TES and solar technology, showing that it lowered environmental impacts by 44% compared to conventional setups, achieving 664 kg CO_2eq/m^2 (or else **28,200** kg CO_{2eq}). On the other hand, Wang et al's (2021) through studying of an optimization model of hybrid solar-assisted CCHP system found the climate change impact much greater than the previous studies (**630,845** kg CO_{2eq}). Figure 36 illustrates the comparison of climate change (kg CO_{2eq}/system) of different systems with MiniStor system installation to demo and replication sites. Generally, all systems range in the same orders of magnitude (10^4 and 10^5). Most sites that MiniStor is installed show lower climate change impact compared to literature systems, highlighting the importance of system configuration and local factors like electricity mix on the climate change impact.

Figure 37 provides a comparison of climate change impacts in terms of kg CO_{2eq}/kWh_{th} for various Thermal Energy Storage (TES) systems among MiniStor system in different sites and literature benchmarks. The MiniStor system generally demonstrates competitive, low-emission performance across most sites. For instance, Thessaloniki and Rome both show a climate impact of 0.05 kg CO_{2eq}/kWh_{th}, comparable to some of the lowest values in the literature. On the contrary, Krakow shows a higher impact at 0.32 kg CO_{2eq}/kWh_{th}, indicating the regional challenges, such as energy mix and regional climate that influence the emissions. Bonamente et al.'s (2020) study that includes PCM-TES system exhibit impact as low as 0.03 kg CO_{2eq}/kWh_{th}. MiniStor's values are comparable, demonstrating the viability of the MiniStor system in competitive climate impact performance. TES systems using Bauxite ceramic and CFA ceramic, achieve extremely low emissions of 0.0018 and 0.0012 kg CO_{2eq}/kWh_{th}, respectively indicative the environmental benefits of using advanced

materials Lalau et al. (2022). Riva et al. (2021) evaluated a hybrid solar absorption system (0.15 kg CO_{2eq}/kWh$_{th}$) and a PV-reversible heat pump (0.07 kg CO_{2eq}/kWh$_{th}$).
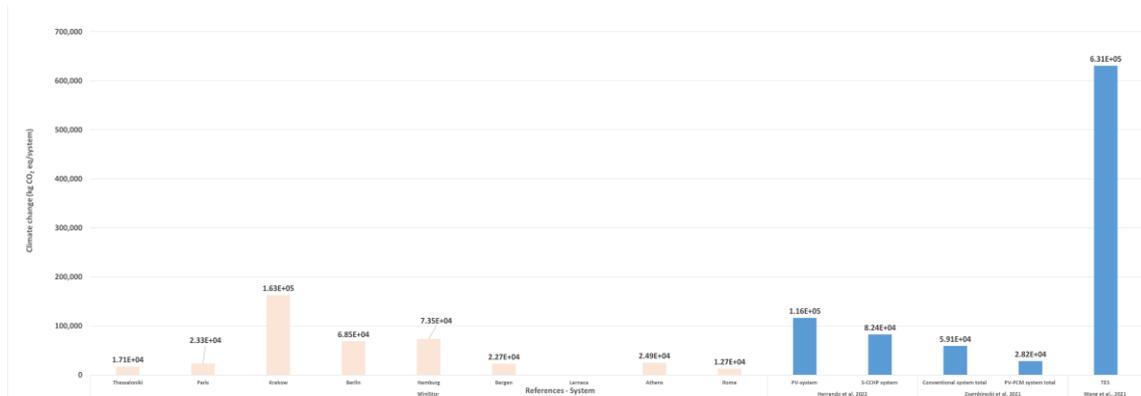
Figure 36. Comparison of climate change (kg CO_{2eq}/system) of the demo and replication sites with selected literature
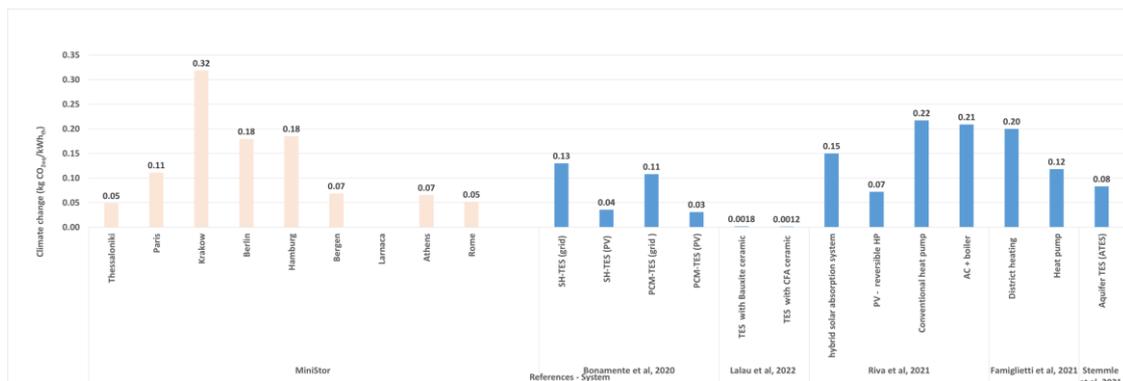
Figure 37. Comparison of climate change (kg CO_{2eq}/kWh$_{th}$) of the demo and replication sites with selected literature

Famiglietti et al. (2021) presented district heating and heat pump systems with climate change impact of 0.20 and 0.12 kg CO_{2eq}/kWh$_{th}$, respectively. MiniStor in most sites shows better performance than Famiglietti's values. Stemmle et al. (2021) studied and Aquifer TES which is an "open-loop geothermal system allowing long-term storage of thermal energy in groundwater" with emissions 0.08 kg CO_{2eq}/kWh$_{th}$, which is very close to MiniStor's impact of Bergen and Athens sites, indicating similar environmental efficiency for aquifer-based TES systems. To conclude, MiniStor's TES systems show a strong environmental performance compared to conventional systems and are competitive with other advanced systems in literature. With opportunities for further emission reduction through innovative materials and configurations, MiniStor demonstrates the potential to support sustainable energy transitions in varied geographic contexts.

4 Life Cycle Cost

4.1 Life Cycle Costing (LCC) methodology

In the framework of D7.3, a Life Cycle Cost Assessment of the proposed integrated system is being conducted to collect all direct and indirect costs associated with its life cycle and investigate the

process with the highest economic contribution. The analysis will provide an initial assessment, from an economic perspective, of the proposed solution and will facilitate comparison with conventional thermal energy storage solutions for domestic needs. The analysis is based on data from the initial demo systems, and as such the results are not directly comparable with mature competing technologies.

Life Cycle Cost (LCC) methodology is based on the widely employed (ISO 14040, 2006) which sets the guidelines for a holistic and comprehensive economic analysis taking into consideration the costs attributed to every life cycle stage. LCC analysis is mainly considered as a financial tool for long-term economic predictions and calculations. ISO 15686-5, (2017) was conducted for further validation by providing guidelines to perform a successful LCC analysis on the construction sector. The LCC analysis is defined as "a methodology for the systematic economic evaluation of life cycle costs over a period of analysis, as defined in the agreed scope". The overall LCC analysis is based on the aggregation of different cost categories as presented below (Eq. 1) and further explained in Table 15.

$$LCC = C_{R\&D} + C_{Aq} + C_{O\&M} + C_{EoL}$$ Equation 1

Table 15. Economic Categories related to LCC

Life Cycle Costs	Cost Sub-Categories	Short Description
Research and Development Costs	Research Studies & Assessments	Costs arising from activities implemented before the start of manufacturing/construction activities.
Acquisition Costs	Materials & Products Supply // Equipment // Construction // Installation // Labour // Transportation & Logistics	Costs relevant to the acquisition of facilities, machinery, equipment, services and other parts of the system that will be installed or constructed.
Operation & Maintenance Costs	Usage // Energy Consumption // Maintenance // Repair // Replacements	Costs arising from the activities that take place during the operation of the facility as well as maintenance, repair and replacement costs of integrated systems, energy systems, parts and equipment, e.g. batteries, sensors etc.
End of Life Costs	Dismantling // Final Disposal // Recycling	End of life costs are costs stemming from project/product demonstration activities after the life of the entire investment, such as waste treatment, metals recycling etc.

5 Baseline Approach

As already mentioned, one demonstration site has been selected for the prototype operation whereas the eight replication sites were selected with the purpose of covering different climatic zones. The scope for the definition of the baseline approach is to assist in quantification the impact from an economic perspective of integrating the MiniStor configuration to each site.

5.1 Demo-site and replication sites energy costs

The cost of energy to cover the annual demands of each site is initially calculated. Necessary info regarding the energy needs for space heating and cooling of each site, the covered and the remaining energy demands have already been presented in Table 10, Table 11 and Table 12.

In the following sub-sections, the calculation of the LCC of Thessaloniki demo and of the replication sites are estimated. The data considered was leveraged from the average cost per energy source for each country, partners' contribution, literature search and necessary assumptions where needed. These investigations can serve as the baseline approach to examine the economic impact of MiniStor integration into existing sites with known energy needs.

The LCC estimation encompasses the acquisition, the operational, the maintenance and end of life costs over the system's lifetime (Eq. 2) or in a simplified version (Eq. 3) (Kehily et al, 2022). This equation derived from the Net Present Value (NPV) approach is used in engineering and economic analysis. Additionally, for comparison purposes, the LCC calculations employ a different approach, where the total costs during the lifetime of the equipment are divided by the total energy consumed over the system's lifetime (Eq.4). In both cases LCC adjusted using the discount rate to account for the time significance of money. Discount rates can range from 3 to 10% (Alpizar et al., 2023) and 5 to 8 % in the energy sector and are usually utilized for estimating NPV in energy evaluations (Lonergan et al, (2023)). According to market risks and country-specific financial conditions, discount rates in the energy sector typically range between 5 and 8% (Steffen, 2020). In the present study, the discount rate is assumed 6% for all locations.

$$LCC = \ CAPEX \ + \sum \frac{O\&M_t}{(1+r)^t} + \frac{EoL}{(1+r)^n} \qquad \text{Equation 2}$$

$$LCC = \ CAPEX \ + NPV_{O\&M} \ + NPV_{EoL} \qquad \text{Equation 3}$$

$$LCC = \frac{CAPEX \ + NPV_{O\&M} \ + NPV_{EoL}}{W_{out}} \qquad \text{Equation 4}$$

where CAPEX stands for the equipment cost (€), $O\&M_t$ for the annual operating and maintenance costs in year t (€), r is the discount rate (annual interest or cost of capital, typically expressed as a decimal), t is the year of expense, n is the system lifetime (y) and EoL is the end of life costs of the system's life (€). Furthermore, the W_{out} is the total energy consumed during the lifetime (kWh).

5.1.1 Thessaloniki Demo site – LCC calculation

The demonstration site located in Thessaloniki, Greece utilizes a high-performance HVAC system to cover the energy demands, according to specifications provided by partners. The necessary assumption to proceed with LCC calculation are:

o HVAC system cost: according to market research the average purchase and installation cost of high-performance HVAC system for domestic needs is approximately 8,000 €

o HVAC Efficiency: a COP of three (3) and an EER of five (5) describe the heating and cooling efficiency of the high-performance HVAC system

o Maintenance costs: HVAC system requires on average 240 €/year for maintenance as estimated 3% of CAPEX (Delač et al 2022). This cost implies functional checks; mainly includes regular cleaning; examining refrigerated lines and gas connections and inspecting fans.

o EoL cost: Considered 7% of CAPEX (Cheung et al., 2015)

o Discount rate: Considered 6% (Steffen, 2020)

o Lifetime: 20 years

Based on the abovementioned considerations, the data from Table 12 and Equation 2, the LCC for Thessaloniki demo site is estimated 20,621 € and 0.06 €/kWh.

Based on Eurostat data (Eurostat, 2024), Table 16 presents the electricity price in Greece and the other countries where the replication sites are located, according to 1st semester 2024 data and the related band of consumption of the sites.

Table 16. Electricity prices for household consumers (€/kWh) in 1st semester 2024

Country	Electricity prices for household consumers (€/kWh)
Greece	0.18
France	0.21
Poland	0.13
Germany	0.25
Norway	0.11
Cyprus	0.21
Italy	0.24

Similar calculations took place for the replication sites serving as the Baseline cases of the LCC analysis. Table 17 summarizes the values of LCC in € and in €/kWh for all selected replication sites.

Table 17. LCC values for the selected sites before MiniStor installation.

Replication Site	LCC (€)	LCC (€/kWh)
Paris	19,339 €	0.09
Krakow	23,639 €	0.05
Berlin	29,168 €	0.08
Hamburg	29,927 €	0.08
Bergen	17,888 €	0.05
Larnaca	21,926 €	0.07
Athens	22,564 €	0.06
Rome	21,792 €	0.09

6 MiniStor system Life cycle cost framework

6.1 Goal and Scope

The goal of the analysis conducted is to examine the economic performance of MiniStor proposed system through its lifecycle for each location examined. The boundaries - include all costs associated with infrastructure, installation, operation and disposal cost of the system. The lifetime of the equipment taken into consideration is 20 years. The functional unit taken into consideration is "*coverage of the annual needs of a standard typical building*" encompassing the fulfillment of the building's heating, cooling, hot water and electricity demand.

Economic data measuring the initial investment (CAPEX) was mainly extracted from D4.5.1 where the costs of main equipment and auxiliary components were presented and direct communication with partners/manufacturers of each sub-system.

6.2 Cost Categories - Inventory

6.2.1 Acquisition Costs

The acquisition costs of MiniStor complete system are based on data compiled from partners/manufacturers communication, D4.5.1 - Figure 13 and literature. Notably, since the battery and inverter have a 10-year lifetime the replacement is necessary within the 20-year system lifetime. Therefore, their costs are doubled in Table 18. Furthermore, the PVT cost corresponds to ten (10) units while the FPC cost accounts for five (5) units that are used in the Thessaloniki pilot site. The solar array includes the cost of the PVT (10 units), the FPC (5 units) and the hydraulics installation and assembly. The BESS encompasses the Li-ion battery and inverter cost, while the MiniStor system includes all other components cost, component assembly cost and the mandatory certifications and safety costs.

Table 18. Acquisition Costs of major MiniStor sub-systems.

MiniStor major sub-systems	Total Cost (€)
Solar **array**	18,633
Container	24,000
Battery Energy Storage System (BESS)	10,960
MiniStor System	98,782
TOTAL	**152,375**

A categorization of the major sub-systems was made to gain insight into their contribution in the total CAPEX as indicated in
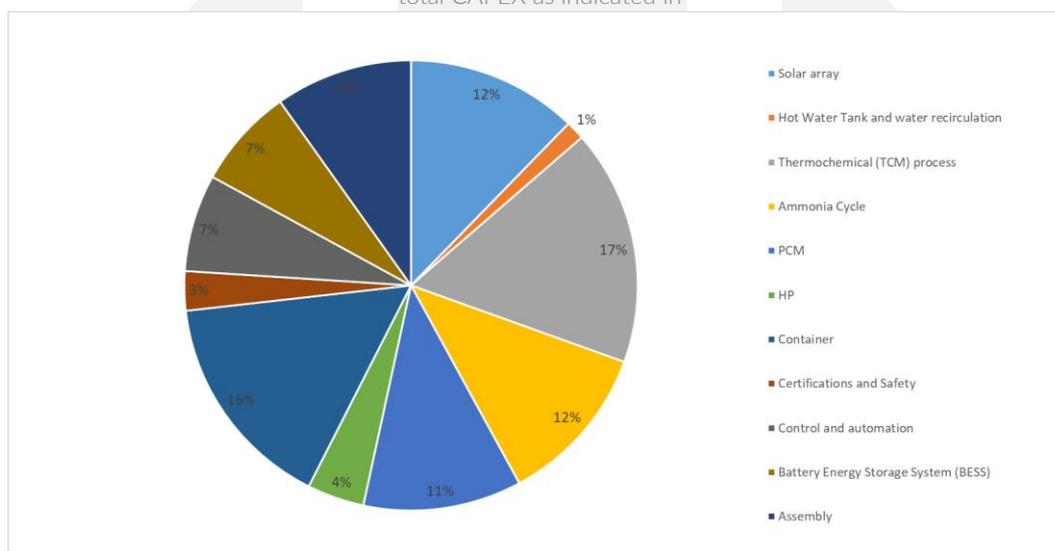
Figure 38.
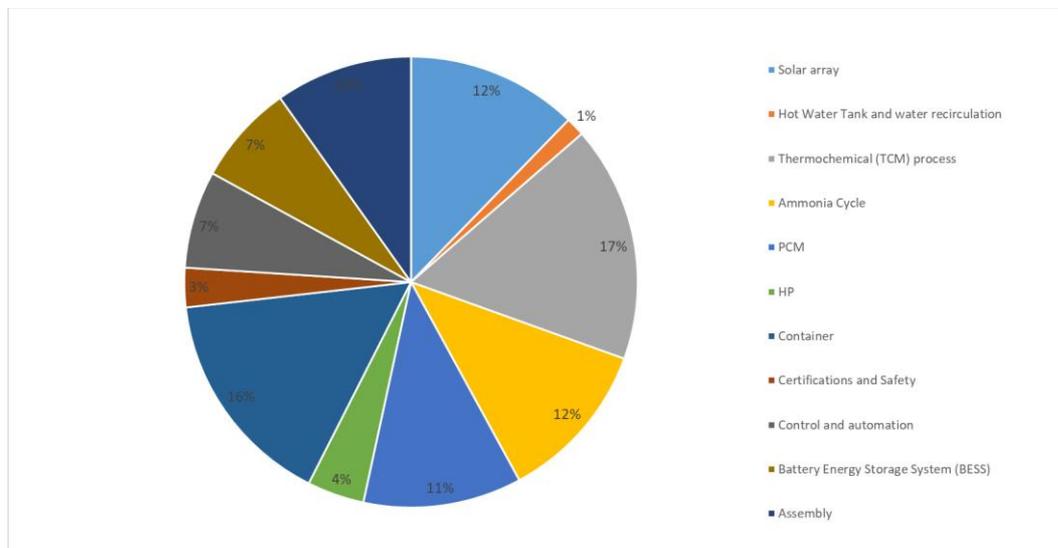
Figure 38. Contribution of each sub-system to total CAPEX.

6.2.2   Research and Development Costs

The Research and Development Costs include all costs relevant to the first stages of investigation, design, improvements and preliminary engineering work before the manufacturing processes and purchases take place. According to literature on LCC analyses taking into consideration R&D costs, a typical percentage is 5-10% of total acquisition costs (Coelho & De Brito, 2013). In the present analysis, since there is no specific guideline, the R&D costs are considered as 10% of total acquisition costs, resulting in a total of 15,238€.

6.2.3   Operation & Maintenance Costs

In this section, the total costs attributed to operation and maintenance of all integrated systems in each house to cover their energy demands are calculated. Data regarding operation conditions, energy coverage by MiniStor, electricity consumption by MiniStor and residual energy covered by previous installations (HVAC) are being provided by relevant partners (Deliverable 2.2) after on-site measurements and have already been presented on Table 10, Table 11 and Table 12. It is deemed necessary to clarify that the residual energy demands after MiniStor installation will continue to be covered by the previous operating system.

In the demo site located in Thessaloniki, according to data provided (Table 12) all energy demands are covered by RES (PV GIS), with no further need of the HVAC system. It is, thus, assumed only the cost for periodic equipment maintenance (500 €/year for MiniStor maintenance based on partner data). Similar conditions are assumed in the case of Larnaca and Rome. In Table 19, the O&M cost for the demo site and for each replication site is estimated considering the O&M of MiniStor and the O&M of HVAC system. This includes the annual electricity required for the demands with MiniStor operation for each site, the electricity price of each country, the lifetime of 20y and the periodic annual costs for MiniStor and HVAC maintenance. The discount rate used in the NPV estimation is considered 6% (Steffen, 2020).

Table 19. Operation and Maintenance costs and their Net Present Value using MiniStor system of Thessaloniki demo site and the eight replication sites

Site	HVAC System O&M (€)	MiniStor maintenance (€)	Total O&M cost (€)	NPV O&M cost (€)

Thessaloniki	-	10,000	10,000	5,735
Paris	13,369	10,000	23,369	11,530
Krakow	23,301	10,000	33,301	28,892
Berlin	29,043	10,000	39,043	22,391
Hamburg	31,515	10,000	41,515	15,229
Bergen	16,971	10,000	26,971	21,813
Larnaca	-	10,000	10,000	5,735
Athens	6,018	10,000	16,018	9,419
Rome	-	10,000	10,000	5,735

6.2.4 End of life Costs

As was previously mentioned, end of life costs are costs occurring from product demonstration activities after the life of the entire investment, such as waste treatment, metals recycling components dismantling and final disposal. Depending on system complexity, the end-of-life cost as a percentage of CAPEX can vary from 5 to 10%. Certain materials (e.g. the PCMs in TES, batteries' materials and solar panels) need specialized disposal techniques to end up being inactive and environmentally friendly, which increases costs. Consequently, the MiniStor system's end of life cost considered 7% of CAPEX since it is an advanced system and not a piece of simple equipment (Cheung et al, 2015).

6.2.5 Total Costs

Table 20 includes the aggregated costs.

Table 20. Total Costs (€)

Cost category (€)	Thessaloniki	Paris	Krakow	Berlin	Hamburg	Bergen	Larnaca	Athens	Rome
Acquisition	152,375								
R & D	15,238								
O & M	10,000	23,369	33,301	39,043	41,515	26,971	10,000	16,018	10,000
End of life	10,666								
Total	188,279	201,648	211,580	217,322	219,794	205,250	188,279	194,297	188,279

7 Cost Assessments Outcomes

Taking into consideration the cost categories analyzed above, the LCC in €/kWh is an appropriate tool to conduct a comparison between demo and replication sites with MiniStor integrated and the Baseline. For the LCC calculation, the total energy discharged from the system to the demo site and each replication site necessitates further explanation, since MiniStor serves simultaneously as thermal and electrical storage and production system. The total amount of heating and cooling demands of the demo site and each replication site, the electrical energy produced from the solar array and the excess electricity fed to the grid was taken into consideration and presented in Table 21. The data are calculated for the whole lifetime of 20 years. It is important to highlight that just

four sites, Thessaloniki, Larnaca, Athens and Rome, have excess electricity and can feed it to the grid.

Table 21. Heating and cooling demands of each site and the electrical energy produced, and the excess energy fed to grid during lifetime

Site	Heating and cooling demands during lifetime (kWh)	Electricity production from PVGIS during lifetime (kWh)	Excess energy fed to grid during lifetime (kWh)	Electricity production from PVGIS – Excess energy fed to grid during lifetime (kWh)
Thessaloniki	349,860	84,400	45,300	39,100
Paris	209,520	64,860		64,860
Krakow	511,500	60,920		60,920
Berlin	381,680	60,020		60,020
Hamburg	397,560	56,060		56,060
Bergen	331,020	43,740		43,740
Larnaca	325,780	93,600	73,500	20,100
Athens	382,040	89,460	69,080	20,380
Rome	246,060	84,900	67,980	16,920

Employing the total costs of MiniStor (Table 20), the O&M and CAPEX of HVAC system considering the electricity values (Table 19) and the heating and cooling demands, the electricity produced and the excess energy fed to the grid for each site (Table 21), the LCC is estimated.**¡Error! No se encuentra el origen de la referencia.** Table 22 summarizes the estimation of LCC adjusted using discount rate (6%) both in € and in €/kWh based on Eq. 3 and Eq. 4 for all the selected sites.

Table 22. LCC values for the selected sites after MiniStor installation.

Site	LCC (€)	LCC (€/kWh)
Thessaloniki	172,957	0.44
Paris	177,872	0.65
Krakow	183,567	0.32
Berlin	186,861	0.42
Hamburg	188,278	0.42
Bergen	179,937	0.48
Larnaca	172,957	0.50
Athens	173,656	0.43
Rome	172,957	0.66

7.1   Feed-in tariffs

Since the LCC analysis determines economic feasibility from an expenditure perspective and is only referred to the evaluation of the total cost of a system over its lifetime without considering its potential revenues (ISO 15686-5, 2017)**,** a second approach of LCC adopted. According to this, the revenues estimation includes the application of the Feed-in Tariff (FiT) leading to the estimation of the LCC_{FiT} using Eq. 5. In certain sites (Thessaloniki, Larnaca, Athens, Rome) the configuration

developed enables the storage (and further usage) of excess electricity produced by the PVGIS and fed to grid. It is relatively safe, thus, to consider that there is an avoided cost due to this surplus energy or else revenue from selling the electricity back to grid. In this case, the average electricity feed-in tariff (Law of Greece 4414/2026; Agathokleous and Kalogirou, 2021; Poponi et al, 2021) of each country for selling electricity from a domestic PV to grid are necessary and presented in Table 23 (retrieved November 4, 2024).

Table 23. Feed-in tariffs for each country where there is an excess of electricity

Country	Feed-in tariffs (€/kWh)
Greece	0.257
Cyprus	0.200
Italy	0.104

$$LCC_{FiT} = LCC - \sum \frac{R_{FiT,t}}{(1+r)^t}$$

Equation 5

where the LCC_{FiT} stands for the Life Cycle Cost with Feed-in Tariff (€), LCC for the Life Cycle Cost considering only expenses which calculated in Table 22¡Error! No se encuentra el origen de la referencia., $R_{FiT,t}$ for the revenue from Feed-in Tariff in year t (€), r for the discount rate (0.06), t is the year of revenue. Table 24 summarizes the annual revenue in four sites in which there is an excess of electricity that fed to grid, as well as the LCC modified by the FiT integration. This integration decreases the total costs by accounting for financial benefits. Comparing the LCC (Table 22) and LCC_{FIT} (Table 24) of MiniStor system, the total MiniStor cost reduced by 4%, 5%, 6% and 2% for Thessaloniki, Larnaca, Athens and Rome, respectively.

Table 24. Annual revenue (€/y) calculation and LCC adjusted to financial benefits (LCC_{FIT}) after MiniStor system installation for the selected sites

Sites	Annual Revenue (€/y)	LCC_FIT MiniStor (€)	LCC_FIT MiniStor (€/kWh)
Thessaloniki	582	166,281	0.43
Paris		177,872	0.65
Krakow		183,567	0.32
Berlin		186,861	0.42
Hamburg		188,278	0.42
Bergen		179,937	0.48
Larnaca	735	164,527	0.48
Athens	898	163,355	0.41
Rome	353	168,903	0.64

8 LCC Interpretation

A thorough Life Cycle Cost Assessment of the proposed MiniStor system was conducted with special focus on all contributions. Baseline approaches were also developed for the demo site of Thessaloniki in addition to the replication sites considering the leveraging building demands and the previously installed equipment to cover the energy needs, to quantify the economic impact of MiniStor installation and operation in a lifespan of 20 years.

Multiple valuable conclusions can be drawn from the intermediate stages of LCC assessment and the final economic impact of MiniStor installation to different climate types, differentiating the energy needs of each site. Figure 39 depicts the contribution of each cost category for Thessaloniki demo site and all the replication sites. It is evident that the very high acquisition costs, including purchases, installation and labor costs, have the highest impact with more than 70% for every case. Furthermore, Thessaloniki, Larnaca and Rome presented the lowest O&M cost contribution. This is attributed to high electricity production of PVGIS which totally covered the building energy demands in addition to MiniStor electricity demands. On the contrary, Krakow, with the highest value of energy demands, necessitates the usage of HVAC system excessively to cover the residual demands, resulting to be one of the three cities with the highest operating costs. Krakow's operational costs are kept in this class because it has the lowest electricity costs among the replication sites; otherwise, Krakow would rank first in terms of operational costs. However, the cities of Germany that have the highest electricity price and seems to have large energy demands, have the greatest percentage of O&M (19% and 18%).

In Figure 40 the comparison of LCC (€/kWh) for the covered energy demands of Thessaloniki demo site and of each replication site before and after MiniStor installation is being presented. Moreover, the modified LCC to the revenues (LCC$_{FiT}$) is also illustrated. The significant difference lies primarily in the very high acquisition costs of MiniStor leading to five to eight times higher LCC for each case. However, it is worth highlighting that the highest LCC values were observed to replication sites with the lowest energy needs, like Paris and Rome.

To put the obtained results into perspective, similar cases focused on LCC calculation for thermal energy storage systems were selected from literature. Venettacci et al. (2022) study can be used as a suitable comparison due to its similarities in the operation and the philosophy of MiniStor proposed system (with the incorporation of PCM materials, the heating and cooling demands' coverage and PV system coupling). Venettacci et al., (2022) performed the environmental and economic assessment of their innovative thermal energy storage based on PCM materials embedded in open-cell copper foams (PF-TES) and coupled with a solar heating and cooling residential system. They made their comparison with a traditional water-based (W-TES) storage with the same capacity. Their results, including analysis on four continents (due to electricity price differentiations) indicated significant differences both between the two investigated systems and by continent. They attributed this high difference (almost 78%) mainly to high manufacturing costs, even though the innovative system presented less operation and maintenance costs, lower auxiliary gas consumption and was less influenced by energy consumption costs.

One of the latest energy storage technologies under investigation is the pumped energy thermal storage (PTES), which can store electrical energy in the form of thermal energy. Tian & Xi, (2022) conducted a comparative analysis of PTES technology with four different organic flash cycles (OFC) and one basic organic Rankine cycle (ORC) as power cycles. Based on their observations the ORC system was proven more suitable to be applied in a PTES system. Figure 41 illustrates the comparison of LCC (€) of MiniStor system with literature TES systems.
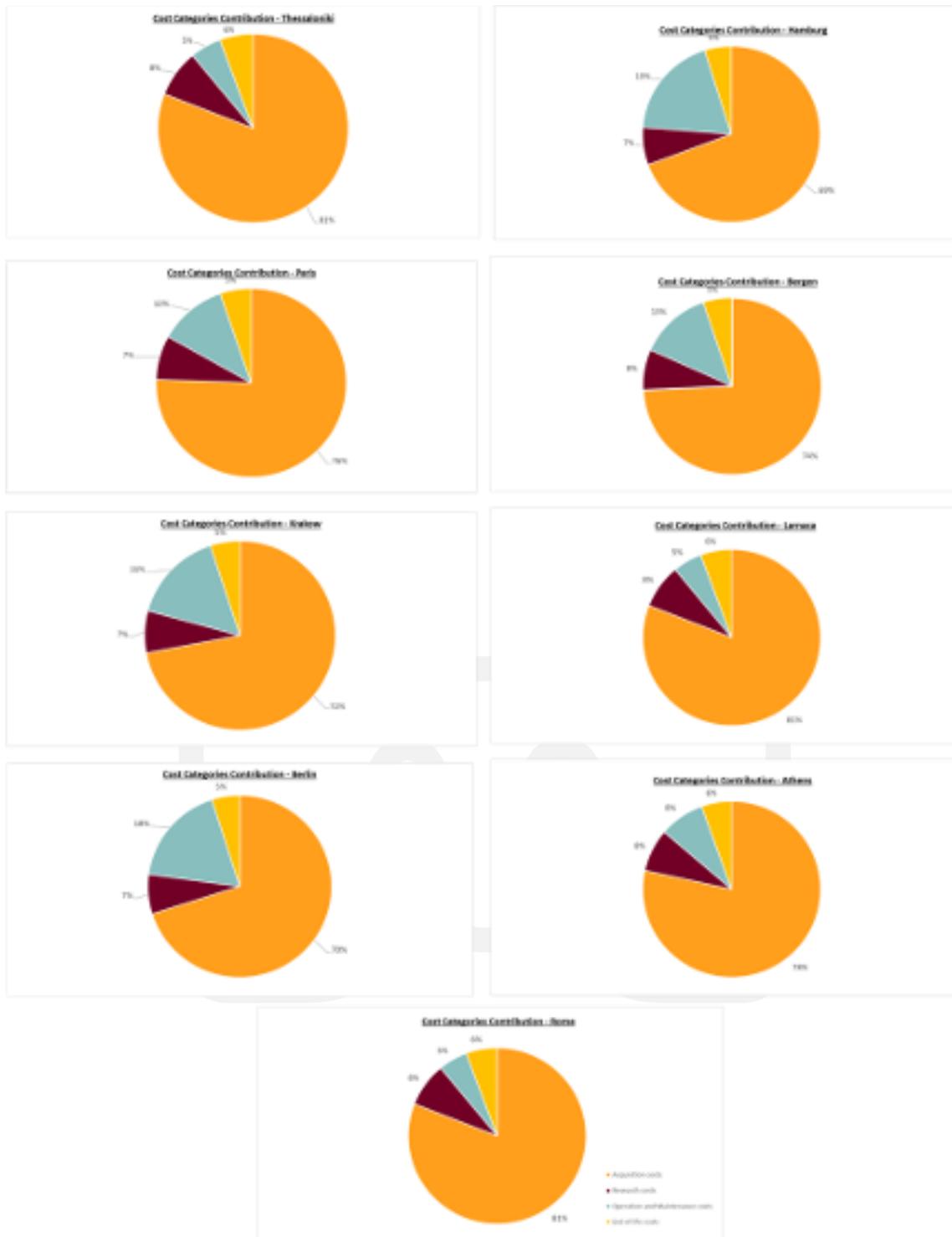
Figure 39. Cost categories contribution to total cost for Thessaloniki demo site and for each replication site through a lifetime of 20 years.
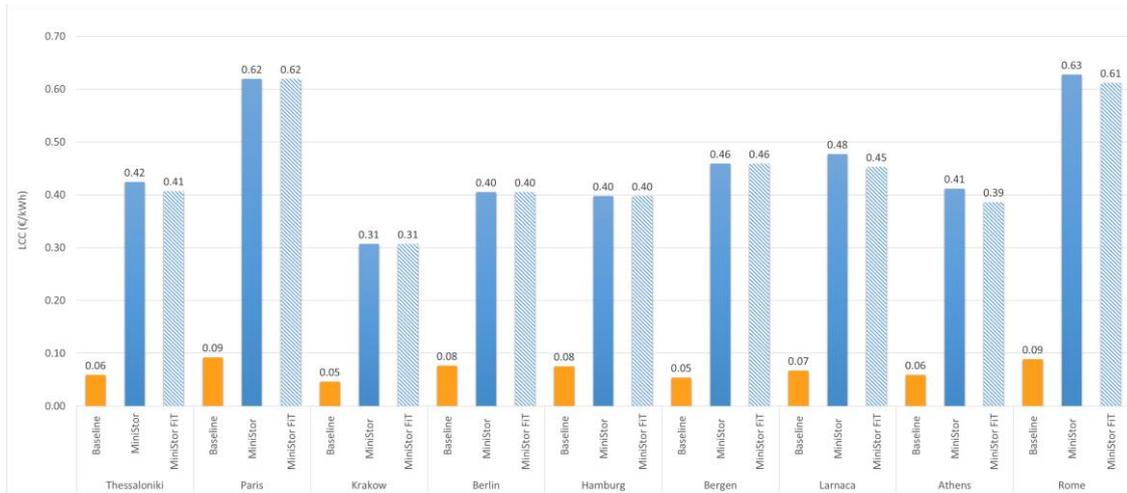
Figure 40. Baseline and MiniStor LCC as well as LCC_FiT values (€/kWh) comparison for demo and each replication site

Furthermore, in case of a cost comparison of different storage systems, it was previously explained that although MiniStor is an ES solution, the LCC metric was calculated (considering the operational phase) to facilitate the comparison with the baseline cases. However, based on the calculation formulas of LCOS and LCOE metrics it is safe to perform the comparison with the literature studies, since all energy discharged in the demo sites has been previously stored in MiniStor. A validation of MiniStor outcomes with selected literature studies is depicted in Figure 42. Indicatively, for a lifetime of 20 years the LCOS of the innovative PF-TES was calculated at 1.69 €/kWh while the same value for the W-TES system was 0.95 €/kWh (Venettacci et al., 2022). Tian et al. presented their LCOS results for all five PTES cases for 398K thermal storage temperature (Tian & Xi, 2022). They observed that system's efficiency and, thus, the LCOS is highly influenced by the thermal storage temperature. For 363K (temperature close to the one that MiniStor stores thermal energy, at 58°C or 342K) the calculated LCOS values were similar or higher than that of MiniStor system (ranging from 0.61 to 0.99 €/kWh). Similarly, Bodner et al., (2023) investigated a PTES system based on a CO_2 charging process. For discharging, an ORC and a CO_2 heat engine was examined. By employing the LCOS cost indicator, the solution with ORC presented the lowest value of 0.59 €/kWh while, on the contrary, the CO_2 discharging process had at 0.82 €/kWh made it less profitable solution. The authors underlined the technological maturity and the importance of further investigations of PTES systems since there are no prototypes yet to implement the technology.
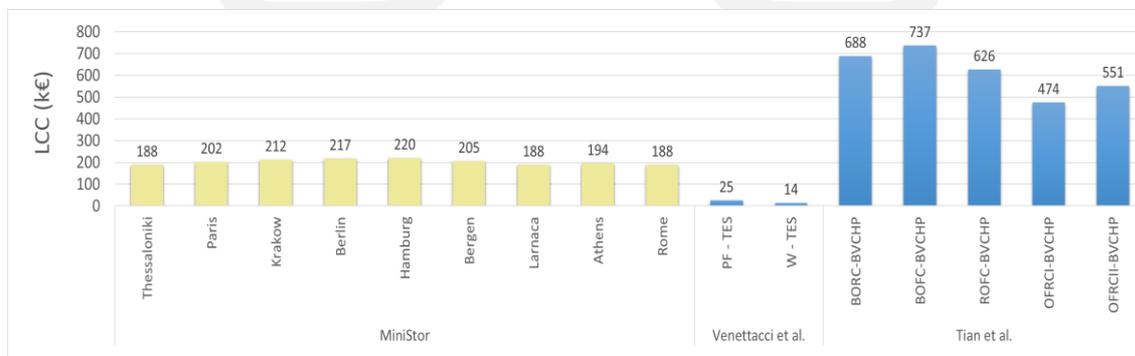

Figure 41. Comparison of MiniStor LCC (€) values with selected literature studies
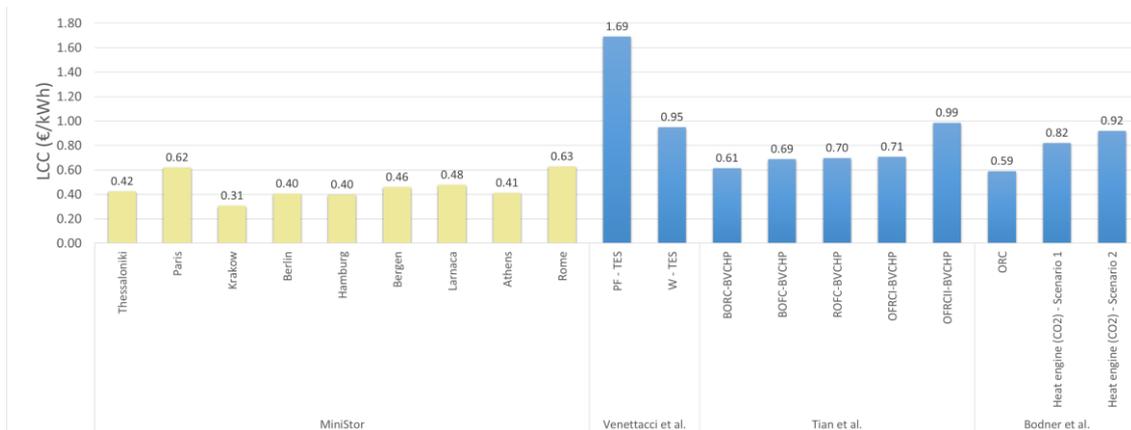
Figure 42. Comparison of MiniStor LCC (€/kWh) values and LCOE (€/kWh) with selected literature studies.

Almost all sites present LCC (€/kWh) and LCOE values close to the ones of LCC investigations with ES solutions like the one developed in MiniStor (Figure 42). It can be concluded that MiniStor would be an economically viable solution if installed to houses with high-energy demands. If coupled with applications of low operational cost, their economic performance is further enhanced. On the contrary, the very high acquisition costs make it an unprofitable solution with relatively low energy demands to be covered.

9 LCC of Conventional technologies

9.1   LCC of Baseline scenarios

Comparison of LCC of conventional types of heating systems to MiniStor

The innovative MiniStor system is compared with the three scenarios of thermal coverage of the building considering the economic assessment, likewise the environmental assessment (section 3.3). The under-investigation scenario 1 is the scenario studied in section 5.1.1. This comparison is performed for Thessaloniki demo site and the replication sites. For every scenario, the baseline and the MiniStor system were compared.

Scenario 2

A light fuel oil boiler with an average thermal efficiency of 80% and an electrically driven heat pump (HVAC) used for heating and cooling, the following necessary assumptions were taken into consideration for the total cost calculation.

- o   Oil boiler cost: an average cost for boiler purchase and installation is 4,500 € according to relevant marker research.

- o   Oil boiler efficiency: In the present case, 80% efficiency is employed.

- o   Oil price: leveraging data from (Global Petrol Prices, 2024) the price of oil in Greece was defined as 1.55€/lt.

- o   Oil fuel: Oil with energy content of approximately 10.39 kWh/lt

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o Oil boiler maintenance cost: The maintenance includes cleaning of burners, checking for leakage signs and corrosion, adjustments of burner settings for efficiency. An average value of 100 € is defined as the annual maintenance cost of the boiler[4].

o Lifetime: 20 years (Lutz et al. 2004)

Adopting the assumptions of Scenario 1 regarding the coverage of cooling demands, which are as follows:

o Heat pump (HVAC) system cost: according to market research an average purchase and installation cost of high-performance HVAC system for domestic needs is approximately 8,000 €

o Heat pump efficiency: EER is five (5) for cooling efficiency of HVAC system

o Maintenance costs: HVAC system requires on average 240 €/year for maintenance as estimated 3% of CAPEX (Delač et al 2022). This cost implies functional checks; mainly includes regular cleaning; examining connections and inspecting fans.

o EoL cost: Considered 7% of CAPEX (Cheung et al., 2015)

o Discount rate: Considered 6% (Steffen, 2020)

o Lifetime: 20 years

Necessary calculations needed to be defined:

o Electricity required: by utilizing the annual heating demands and the EER of the heat pump it is calculated that the electricity required is 1,704 kWh/y for Thessaloniki demo site.

o Energy required from oil boiler = Heating demands annually/ efficiency = 8,973 kWh /y / 0.8 = 11,216 kWh /y

o Oil cost = Oil cost (*Greece*) / Oil energy content= 1.55 €/lt / 10.39 kWh/lt = 0.15 €/kWh

o Heating Cost = Energy required * Oil cost = 11,216 kWh/y * 0.15 €/kWh = 1,673 €/y or total heat cost from the oil boiler 33,465 € during lifetime.

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[4] https://www.checkatrade.com/

Table 25 presents the oil prices based on (Global Petrol Prices, 2024), the annual heat cost for each site in addition to the total heat cost from oil boiler during lifetime before the MiniStor installation.

Table 25. Oil fuel prices (Global Petrol Prices, 2024)

Site	Oil prices (€/lt)	Oil cost (€/kWh)	Heat cost (€/y)
Thessaloniki	1.550	0.15	1,673
Paris	1.619	0.16	2,041
Krakow	1.403	0.14	4,317
Berlin	1.559	0.15	3,579
Hamburg	1.559	0.15	3,728
Bergen	1.637	0.16	3,260
Larnaca	1.444	0.14	1,705
Athens	1.550	0.15	2,539
Rome	1.649	0.16	2,211

According to the abovementioned assumptions, the electricity price (Eurostat, 2024) (Table 16), the simulated data from D3.1 and D6.7 and the calculations based on the Eq. 2, Eq. 3 and Eq. 4, the LCC in € and in €/kWh for the demo site and for all selected replication sites is summarized in Table 26 for the baseline case.

Table 26. LCC values (€) for the selected sites before MiniStor installation.

Site	LCC of oil boiler (€)	LCC of HVAC system (€)	LCC total (€)	LCC of oil boiler (€/kWh)	LCC of HVAC system (€/kWh)	LCC total (€/kWh)
Thessaloniki	24,937	14,445	39,383	0.07	0.04	0.11
Paris	29,150	10,927	40,077	0.14	0.05	0.19
Krakow	55,259	10,927	66,187	0.11	0.02	0.13
Berlin	46,801	10,927	57,728	0.12	0.03	0.15
Hamburg	48,509	10,927	59,436	0.12	0.03	0.15
Bergen	43,133	10,927	54,060	0.13	0.03	0.16
Larnaca	25,297	14,048	39,344	0.08	0.04	0.12
Athens	34,872	13,192	48,064	0.09	0.03	0.13
Rome	31,108	11,564	42,672	0.13	0.05	0.17

Scenario 3

A natural gas boiler with an average thermal efficiency of 90% provides heating, while an electrically driven heat pump handles cooling. The required assumptions were made regarding the overall cost calculation.

o   Natural gas boiler cost: an average cost for boiler purchase and installation is 2,500€ according to relevant marker research.

o   Natural gas boiler efficiency: modern boilers have an efficiency factor of over 90%. In the present case, 90% efficiency is employed.

o   Natural gas price for households: leveraging data from the price of gas in Greece was defined as 0.06 €/kWh.

o Natural gas boiler maintenance cost: An average value of 120 € is defined as the annual maintenance cost of the boiler. This cost involves boiler's inspection, functionality check, leak check and test the flue gases in case of toxic fumes.

o Lifetime: 20 years

Adopting the assumptions of Scenario 1 regarding the coverage of cooling demands, which are as follows:

o Heat pump (HVAC) system cost: according to market research an average purchase and installation cost of high-performance HVAC system for domestic needs is approximately 8,000 €

o Heat pump efficiency: EER is five (5) for cooling efficiency of HVAC system

o Maintenance costs: HVAC system requires on average 240 €/year for maintenance as estimated 3% of CAPEX (Delač et al 2022). This cost implies functional checks; mainly includes regular cleaning; examining connections and inspecting fans.

o EoL cost: Considered 7% of CAPEX (Cheung et al., 2015)

o Discount rate: Considered 6% (Steffen, 2020) and a Lifetime: 20 years

Necessary calculations needed to be defined:

o Electricity required: by utilizing the annual heating demands and the EER of the heat pump it is calculated that the electricity required is 1,704 kWh/y for Thessaloniki demo site.

o Heating Cost = Energy required * NG cost = 9,970 kWh/y * 0.06 €/kWh = 598 €/ kWh or total heat cost from the gas boiler 11,964 € during lifetime.

Table 27 presents the average natural gas prices for households (*based on March 2024*) according to (Global Petrol Prices, 2024), the annual heat cost for each site in addition to the total heat cost from natural gas boiler during lifetime before the MiniStor installation. In case of Bergen (Norway) data is limited and based on the year 2020 while natural gas information for Larnaca (Cyprus) is not available probably due to Cyprus having minimal infrastructure for natural gas distribution, leading to low percentage of use.

Table 27. Natural gas prices (Global Petrol Prices, 2024)

Site	NG prices (€/kWh)	Heat cost annually (€/y)
Thessaloniki	0.060	598
Paris	0.111	1,292
Krakow	0.086	2,444
Berlin	0.086	1,824
Hamburg	0.086	1,899
Bergen[5]	0.007	138
Larnaca[6]	-	-
Athens	0.060	908
Rome	0.136	1,684

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[5] Based on 2020 data (www.intratec.us)

[6] No data found

According to the abovementioned assumptions, the electricity price (Eurostat, 2024) (Table 16), the simulated data from D3.1 and D6.7 and the calculations based on the Eq. 2, Eq. 3 and Eq. 4, the LCC in € and in €/kWh for the demo site and for all selected replication sites regarding scenario 3 is summarized in Table 28 for the baseline case.

Table 28. LCC values for the selected sites before MiniStor installation.

Site	LCC of NG boiler (€)	LCC of HVAC system (€)	Total LCC (€)	LCC of NG boiler (€/kWh)	LCC of HVAC system (€/kWh)	Total LCC (€/kWh)
Thessaloniki	10,792	16,412	27,205	0.03	0.05	0.08
Paris	18,751	24,371	43,121	0.09	0.12	0.21
Krakow	31,962	37,582	69,543	0.06	0.07	0.14
Berlin	24,847	30,467	55,315	0.07	0.08	0.14
Hamburg	25,718	31,338	57,055	0.06	0.08	0.14
Bergen	5,511	11,131	16,641	0.02	0.03	0.05
Larnaca	3,931	9,551	13,482	0.01	0.03	0.04
Athens	14,344	19,964	34,308	0.04	0.05	0.09
Rome	23,250	28,870	52,119	0.09	0.12	0.21

9.2   LCC of MiniStor system scenarios

By following the same steps outlined in **section** 6.2.3, the total operation and maintenance costs after the MiniStor system installation across all sites to meet their energy demands are summarized in Table 29 under Scenario 2 and in Table 31 under Scenario 3. Moreover, the NPV was estimated considering a 6% discount rate (Steffen, 2020). According to the abovementioned assumptions, the electricity price (Eurostat, 2024) (Table 16), the simulated data from D3.1 and D6.7 and the calculations based on the Eq. 2, Eq. 3 and Eq. 4, the LCC in € and in €/kWh for the demo site and all the selected replication sites is summarized in Table 30 for the MiniStor case. Any excess electricity generated by the PVT system is fed into the local grid therefore the modified LCC by the annual revenue (LCC$_{FIT}$) using Eq. 5 and Table 23 presented in Table 30. The LCC with and without revenue concerning scenario 3 is presented in

Table 32. It is worth mentioning that the inclusion of revenue in both scenarios result in a 2% – 5% decrease in LCC regarding Thessaloniki, Athens, Larnaca and Rome.

Table 29. Operation and Maintenance costs and their Net Present Value using MiniStor for Thessaloniki demo site and the eight replication sites under Scenario 2

Site	Oil boiler O&M (€)	HVAC System O&M (€)	MiniStor maintenance (€)	Total O&M cost (€)	NPV O&M cost (€)
Thessaloniki	13,405	4,800	10,000	28,205	16,175
Paris	22,608	5,963	10,000	38,571	22,120
Krakow	65,820	6,916	10,000	82,737	47,449
Berlin	52,300	6,695	10,000	68,995	9,568
Hamburg	55,522	7,735	10,000	73,257	42,013

Bergen	50,854	7,876	10,000	68,730	39,416
Larnaca	22,548	4,800	10,000	37,348	21,419
Athens	36,170	4,800	10,000	50,970	29,231
Rome	30,627	4,800	10,000	45,427	26,052

Table 30. LCC (€ and (€/kWh), annual revenue (€/y) and LCC adjusted to financial benefits (LCC$_{FIT}$) after MiniStor system installation for the selected sites.

Site	LCC (€)	LCC (€/kWh)	Annual Revenue (€/y)	LCC$_{FIT}$ (€)	LCC$_{FIT}$ (€/kWh)
Thessaloniki	184,649	0.47	582	177,972	0.46
Paris	190,594	0.68	-	190,594	0.68
Krakow	215,923	0.37	-	215,923	0.37
Berlin	208,042	0.46	-	208,042	0.46
Hamburg	210,486	0.45	-	210,486	0.45
Bergen	207,890	0.52	-	207,890	0.52
Larnaca	189,893	0.55	735	181,462	0.52
Athens	197,705	0.49	888	187,523	0.47
Rome	194,526	0.74	353	190,471	0.72

For each scenario, the LCC for the covered energy demands of Thessaloniki demo site and each replication site was estimated before and after the MiniStor installation. The comparison of LCC (€) across the three scenarios (HP, oil boiler and HP, NG boiler and HP) under baseline case and under MiniStor system case for the Thessaloniki demo site and the replication sites during the lifetime is presented in Figure 43. As already been noticed, in the first scenario, in which only the is HP used, the LCC of the MiniStor system is significantly higher than the baseline LCC. This suggests that, while MiniStor provides benefits such as increased storage and grid flexibility, it introduces additional costs associated with the acquisition costs. For example, in Thessaloniki, the LCC for use of HP only illustrates nearly 8-fold increase as increases from 20,621€ (Baseline) to 172,957 € (MiniStor). In Figure 44 the LCC comparison of each scenario in €/kWh is provided.

Table 31. Operation and Maintenance costs and their Net Present Value using MiniStor for Thessaloniki demo site and the eight replication sites under Scenario 3

Site	NG boiler O&M (€)	HVAC System O&M (€)	MiniStor maintenance (€)	Total O&M cost (€)	NPV O&M cost (€)
Thessaloniki	6,477	4,800	10,000	21,277	12,202
Paris	15,449	5,963	10,000	31,412	18,015
Krakow	38,530	6,916	10,000	55,446	31,798
Berlin	28,026	6,695	10,000	44,721	25,647
Hamburg	29,668	7,735	10,000	47,403	27,185
Bergen	4,464	7,876	10,000	22,340	12,812
Larnaca	2,400	4,800	10,000	17,200	9,864
Athens	14,616	4,800	10,000	29,416	16,870
Rome	24,205	4,800	10,000	39,005	22,369

Table 32. LCC (€ and (€/kWh), annual revenue (€/y) and LCC adjusted to financial benefits (LCC$_{FiT}$) after MiniStor system installation for the selected sites.

Site	LCC (€)	LCC (€/kWh)	Annual Revenue (€/y)	LCC$_{FIT}$ (€)	LCC$_{FIT}$ (€/kWh)
Thessaloniki	178,632	0.46	582	171,956	0.44
Paris	184,445	0.66	-	184,445	0.66
Krakow	198,228	0.34	-	198,228	0.34
Berlin	192,077	0.43	-	192,077	0.43
Hamburg	193,615	0.42	-	193,615	0.42
Bergen	179,242	0.45	-	179,242	0.45
Larnaca	176,294	0.51	735	167,864	0.49
Athens	183,300	0.46	898	173,118	0.43
Rome	188,799	0.72	353	184,745	0.70

The scenario of using only the HP has the lowest Baseline LCC compared to setups involving oil and natural gas boilers. This indicates that heat pumps are a more cost-effective option for heating. However, after MiniStor installation, the LCC in case of HP only rises sharply in all cities and, becoming comparable across scenarios and significantly more expensive than baseline HP cost. Furthermore, natural gas boilers and HP combination are often less expensive than the oil boiler and HP scenario regarding baseline cases. It is worth mentioning that Bergen, Thessaloniki and Larnaca exhibit relatively lower baseline LCC in the HP scenario due to lower local electricity prices and milder climates that reduce heating demands. On the other hand, Krakow, Berlin, and Hamburg show higher LCC values, reflecting higher energy demands in colder climates.

Taking into consideration the revenue generated from selling the excess electricity produced by the solar array back to the grid, the lowest LCC after MiniStor installation is observed in the HP scenario in Athens, Larnaca, Thessaloniki and Rome in ascending order. In Annex II Figure 32 illustrated the comparison of LCC (€) and LCC (€) with revenue included for each scenario, in both baseline and the MiniStor system case across, all sites over the lifetime.
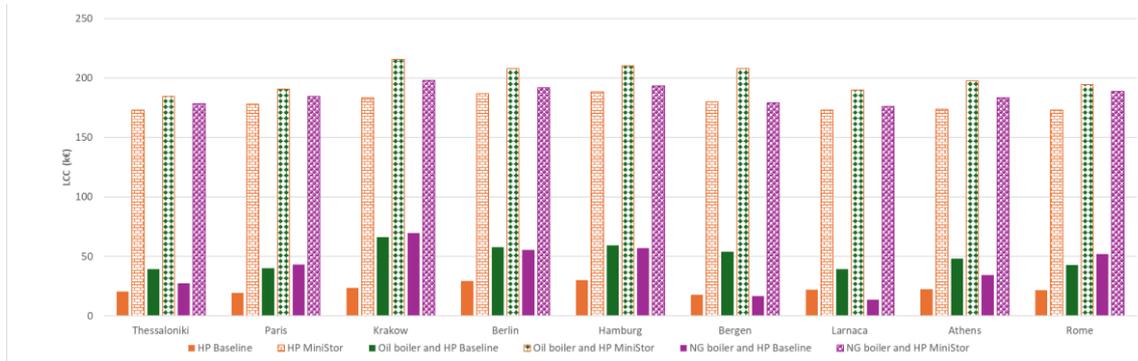
Figure 43. Comparison of LCC (€) for each scenario (HP: orange, oil boiler and HP: green and NG boiler and HP: purple) in baseline case and in the MiniStor system case for Thessaloniki demo site and the replication sites over the lifetime
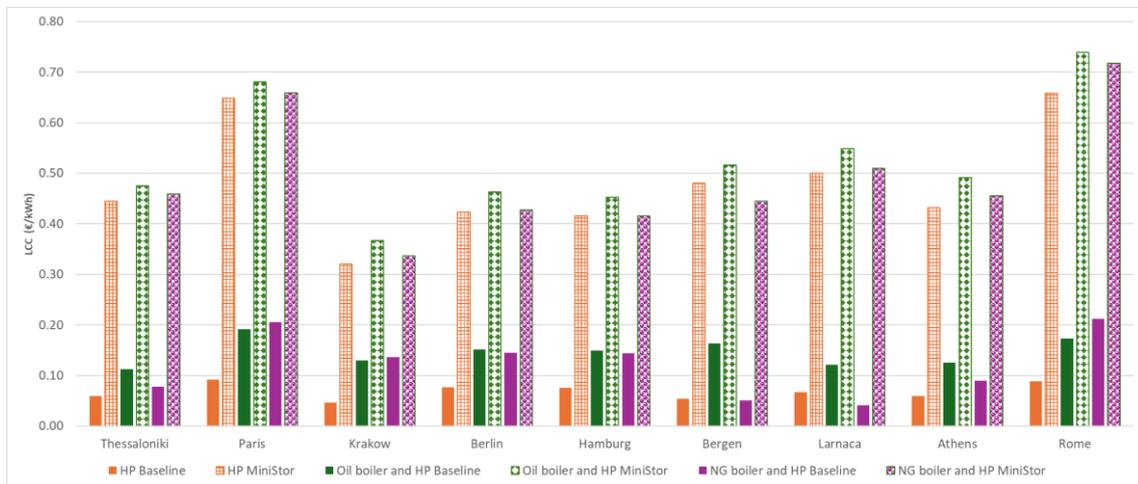

Figure 44. Comparison of LCC (€/kWh) for each scenario (HP: orange, oil boiler and HP: green and NG boiler and HP: purple) in case of the baseline and in case of MiniStor system installation for Thessaloniki demo site and the replication sites over the lifetime

10   Conclusions

This report presented a sustainability assessment from environmental, economic, and social perspectives. Specifically, it included a detailed Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis of the innovative MiniStor system, which is designed to provide cooling, heating, and domestic hot water (DHW) in residential buildings across various European locations with different climatic conditions, thermal load needs, energy mixes, and costs.

The Life Cycle Inventory (LCI) of the system covers the material mass of components and the energy required for manufacturing and installation. LCI data were derived from component manufacturers, technical brochures, literature, and the Ecoinvent database where direct data were unavailable. Operational data for the Thessaloniki demo site were obtained through on-site measurements, while simulations were conducted for eight additional European replication sites.

The LCA focused primarily on climate change, fossil and nuclear energy use, and water scarcity. During the manufacturing phase, the MiniStor metallic container (27%), solar collector area (18%), and lithium-ion (Li-ion) battery of the Battery Energy Storage System (BESS) (14%) emerged as the main contributors to climate change. The significant impact of the metallic container and solar area on fossil and nuclear energy use indicates substantial reliance on non-renewable sources during

their production. The solar-assisted unit (solar collector, hot water tank, and associated infrastructure), which weighs nearly one ton, contributes 32% to the overall climate change impact. Additionally, the Li-ion battery accounts for 59% of the water scarcity impact, likely due to water use during its manufacturing.

When comparing the baseline (pre-MiniStor installation) with the post-installation MiniStor system, results indicate a decrease in overall climate change impact across most sites. This improvement is primarily due to the operational phase of the MiniStor system, which offsets the higher environmental burden of its manufacturing phase. At the Thessaloniki demo site, the infrastructure was the primary contributor to environmental impacts across all midpoint categories; however, the operation is fully powered by renewable energy sources (RES), which significantly reduces the long-term impact.

A sensitivity analysis evaluating integration with conventional heating systems (heat pump, oil boiler, and natural gas boiler) showed that the MiniStor system reduces environmental impacts regardless of the heating method used. At the Thessaloniki site, MiniStor reduced total climate change impact by 76%, 73%, and 75% when paired with a heat pump, oil boiler, and natural gas boiler, respectively.

In conclusion, MiniStor's thermal energy storage (TES) systems exhibit strong environmental performance compared to conventional systems and are competitive with other advanced solutions in the literature. There is further potential for emission reduction using innovative materials and improved configurations. Thus, MiniStor shows promise for supporting sustainable energy transitions across diverse geographic contexts. However, from a social perspective, significant barriers to widespread adoption remain, particularly in the areas of manufacturing, end-of-life stages, and the availability of specialized professional expertise.

A comprehensive LCC analysis of MiniStor applications at various sites was also conducted, accounting for different life cycle stages, economic inputs from partners and manufacturers, and comparisons with both baseline cases and other energy storage solutions reported in the literature, as a steppingstone for the Business Models that will be developed in WP7. This analysis highlighted both economic advantages and challenges. While MiniStor improves heating system flexibility, it increases LCC across all sites and configurations, mainly due to high acquisition and installation costs, which are to be expected for the TRL level and the production of prototypes. Among conventional systems, heat pumps generally perform best in both baseline and MiniStor scenarios. Natural gas boilers paired with heat pumps present a comparatively lower LCC than oil boiler combinations, due to the higher fuel and maintenance costs of oil systems.

MiniStor's economic impact also varies by location. In milder climates with lower heating demand and relatively low energy prices, total costs are reduced. Incorporating revenue from excess electricity into the LCC analysis led to a modest reduction in total LCC, between 2% and 5% across all scenarios.

In general, both the environmental and the economic evaluation of the prototypes in various locations suggests a promising direction for further exploration of ammonia as an energy storage medium. Ammonia's unique characteristics may offer profitable pathways when compared to other media such as hydrogen, despite the upfront costs associated with equipment and maintenance.

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Annex I

Annex I Table 1. Categories of components based on data type and derived source

Component	Group categories	Data type	Source
Photovoltaic thermal collectors (PVT)	Solar assisted unit /Solar area	Primary	ENDEF
Flat Plate Collector (FPC)	Solar assisted unit /Solar area	Primary	ENDEF
Hot water tank (buffer tank) with heater	Solar assisted unit	Primary	ENDEF
Metallic structures to support the solar collectors	Remaining infrastructure	Primary	ENDEF
Piping	Remaining infrastructure	Primary	ENDEF
Electrical cables	Remaining infrastructure	Primary	ENDEF
Thermochemical material reactor (TCM)	MiniStor system	Primary	Deliverable 4.3 (Sunamp)
Ammonia Compressor	Ammonia cycle / MiniStor system	Secondary	Ecoinvent database
Oil Separator	Ammonia cycle / MiniStor system	Primary	OSC COLD manufacturer brochure
Lubricating oil	Ammonia cycle / MiniStor system	Secondary	Ecoinvent database
Heat transfer fluid	Ammonia cycle / MiniStor system	Primary	ENDEF / PSYCTOTHERM
Ammonia Condenser	Ammonia cycle / MiniStor system	Primary	manufacturer brochure (Spirec; online)
Ammonia Evaporator	Ammonia cycle / MiniStor system	Primary	manufacturer brochure (Spirec; online)
Liquid Ammonia tank	Ammonia cycle / MiniStor system	Primary	PHYCTOTHERM
Heat Pump	Heat pump / MiniStor system	Secondary	Ecoinvent database

HOT PCM	PCM/ MiniStor system	Primary and secondary	Deliverable 4.3; manufacturer brochure (Sunamp)
COLD PCM	PCM/ MiniStor system	Primary and secondary	Deliverable 4.3; manufacturer brochure (Sunamp)
HOT DHW	PCM/ MiniStor system	Primary and secondary	Deliverable 4.3; manufacturer brochure (Sunamp)
MiniStor metallic container	MiniStor system	Primary	PHYCTOTHERM
Pumps (four)	MiniStor system	Secondary	Ecoinvent database
Control unit	MiniStor system	Primary	PHYCTOTHERM
Lithium-Iron-Phosphate battery	BESS / MiniStor system	Secondary	Ecoinvent database
Hybrid solar inverter	BESS / MiniStor system	Primary	PHYCTOTHERM
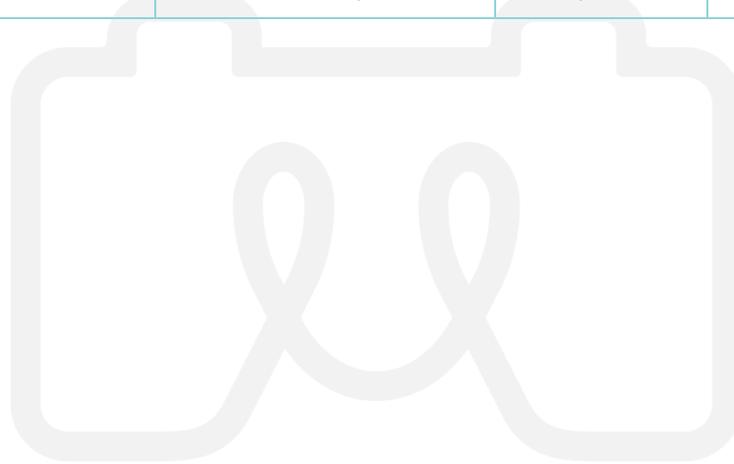
Annex II

Environmental Impact Assessment

The following tables present the outcomes of the environmental assessment regarding the three main impact categories (climate change, long term, Fossil and nuclear energy use and water scarcity during the manufacturing stage.

Annex II Table 1. Environmental assessment of one PVT glazed during manufacturing stage

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m3 world eq
Total	2.40E+02	2.99E+03	1.31E+02
Solar glass, low-iron {GLO}| market for | Cut-off, U	2.73E+01	3.39E+02	5.58E+00
Silicone product {RoW}| market for silicone product | Cut-off, U	2.08E+00	3.85E+01	3.15E+00
Metallization paste, front side {RER}| market for metallization paste, front side | Cut-off, U	1.07E+00	1.61E+01	2.97E-01
Aluminium, wrought alloy {GLO}| market for | Cut-off, U	9.33E+01	9.88E+02	1.29E+01
Copper, cathode {GLO}| market for | Cut-off, U	5.90E+01	8.08E+02	8.10E+01
Glass wool mat {GLO}| market for | Cut-off, S	5.82E+00	9.98E+01	2.54E+00
Polypropylene, granulate {GLO}| market for | Cut-off, U	1.65E-02	6.57E-01	7.50E-03
Metal working, average for aluminium product manufacturing {RoW}| processing | Cut-off, U	2.83E+01	3.33E+02	4.32E+00
Metal working, average for copper product manufacturing {RER}| processing | Cut-off, U	2.36E+01	3.68E+02	2.08E+01

Annex II Table 2. Environmental assessment of solar assisted unit during manufacturing stage (one 1.55 m^2 PVT and one 2.37 m^2 FPC)

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m3 world eq
Total	3.20E+03	4.02E+04	1.33E+03
Photovoltaic Thermal Collector (PVT) 260W	2.41E+02	3.00E+03	1.31E+02
Solar thermal Flat Plate Collectors (FPC)	2.52E+02	3.01E+03	9.37E+01
Inertia-buffer water tank	1.12E+02	1.64E+03	5.03E+01
Auxiliary heater	2.17E+00	3.11E+01	2.63E+00
Metallic structures to support the solar collectors' blocks	2.00E+03	2.31E+04	3.68E+02
Piping	5.03E+02	7.90E+03	5.75E+02
Electrical cables	8.92E+01	1.48E+03	1.09E+02

Annex II Table 3. Environmental assessment of solar assisted unit during manufacturing stage in the case of Thessaloniki (10 PVT and 5 FPC)

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m3 world eq
Total	6.37E+03	7.92E+04	2.88E+03
Photovoltaic Thermal Collector (PVT) 260W	2.41E+03	3.00E+04	1.31E+03
Solar thermal Flat Plate Collectors (FPC)	1.26E+03	1.51E+04	4.69E+02
Inertia-buffer water tank	1.12E+02	1.64E+03	5.03E+01
Auxiliary heater	2.17E+00	3.11E+01	2.63E+00
Metallic structures to support the solar collectors' blocks	2.00E+03	2.31E+04	3.68E+02
Piping	5.03E+02	7.90E+03	5.75E+02
Auxiliary heater	8.92E+01	1.48E+03	1.09E+02

Annex II Table 4. Environmental assessment during manufacturing stage for the thermochemical material reactor (TCM) with the salt $CaCl_2$ and graphite material

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m^3 world eq
Total	9.15E+02	1.29E+04	3.79E+02
Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	1.16E+02	1.47E+03	4.11E+01
Steel, chromium steel 18/8, hot rolled {GLO}| market for | Cut-off, U	4.66E+02	5.94E+03	1.89E+02
Calcium chloride {RER}| market for calcium chloride | Cut-off, U	1.65E+01	2.10E+02	3.36E+01
Graphite {GLO}| market for | Conseq, U	4.06E-01	5.68E+00	7.52E-02
Metal working, average for chromium steel product manufacturing {RER}| processing | Cut-off, U	1.65E+02	2.54E+03	5.34E+01
Welding, arc, steel {RER}| processing | Cut-off, U	1.01E+00	1.56E+01	6.90E-01
Sheet rolling, steel {RoW}| processing | Cut-off, U	7.28E+00	9.96E+01	5.85E+00
Tube insulation, elastomere {GLO}| market for | Cut-off, U	4.37E+01	1.15E+03	2.32E+01

Annex II Table 5. Environmental assessment of the heat transfer fluid circulated in MiniStor system

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m3 world eq
Total	2.11E+02	5.23E+03	2.33E+02
Water, deionised {Europe without Switzerland} | water production, deionised | Cut-off, U	7.26E-02	1.14E+00	7.86E+00
Propylene glycol, liquid {RER}| market for propylene glycol, liquid | Cut-off, U	2.11E+02	5.22E+03	2.25E+02

Annex II Table 6. Environmental assessment during manufacturing stage for the ammonia cycle components

Impact category	Unit	Ammonia compressor, 4 kW	Ammonia Condenser, 4 kW	Ammonia Evaporator, 3 kW	Oil separator	Lubricating oil	Liquid ammonia tank
Climate change, long term	kg CO_{2eq}	8.25E+02	3.46E+01	3.60E+01	5.77E-01	7.80E-01	1.32E+02
Fossil and nuclear energy use	MJ deprived	1.09E+04	4.70E+02	4.74E+02	7.47E+00	4.60E+01	1.85E+03
Water scarcity	m3 world eq	3.78E+02	1.28E+01	1.27E+01	2.51E-01	2.60E-01	4.36E+01

Annex II Table 7. Environmental assessment during manufacturing stage for heat pump

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m3 world eq
Total	2.05E+02	1.81E+03	7.12E+01
Heat pump, 30kW {GLO}| market for	Cut-off, U	1.96E+02	1.74E+03	6.84E+01
Metal working, average for steel product manufacturing {GLO}| market for	Cut-off, U	1.12E+00	1.58E+01	2.57E-01
Refrigerant R134a {GLO}| market for	Cut-off, U	7.08E+00	5.55E+01	2.58E+00

Annex II Table 8. Environmental assessment during the manufacturing stage for the Hot PCM

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m3 world eq
Total	1.03E+03	1.12E+04	1.55E+02
SU-58 PCM	4.09E+01	1.05E+03	1.53E+01
Aluminium, wrought alloy {GLO}| market for | Cut-off, U	9.44E+02	9.37E+03	1.23E+02
Glass wool mat {GLO}| market for | Cut-off, U	6.22E+00	9.90E+01	2.51E+00
Polypropylene, granulate {RoW}| production | Cut-off, U	7.07E+00	2.45E+02	2.50E+00
Metal working, average for steel product manufacturing {GLO}| market for | Cut-off, U	9.49E+00	1.22E+02	1.99E+00
Steel, chromium steel 18/8 {GLO}| market for | Cut-off, U	2.30E+01	2.73E+02	7.63E+00
Sheet rolling, chromium steel {GLO}| market for | Cut-off, U	2.91E+00	4.02E+01	1.87E+00

Annex II Table 9. Environmental assessment during manufacturing stage for Cold PCM

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m^3 world eq
Total	1.49E+03	1.25E+04	1.92E+02
SU-11 PCM	1.40E+03	1.12E+04	1.70E+02
Aluminium, wrought alloy {GLO}| market for	Cut-off, U	4.51E+01	4.77E+02	6.26E+00
Glass wool mat {GLO}| market for	Cut-off, U	5.77E+00	9.90E+01	2.51E+00
Polypropylene, granulate {RoW}| production	Cut-off, U	6.14E+00	2.45E+02	2.50E+00
Metal working, average for steel product manufacturing {GLO}| market for	Cut-off, U	8.66E+00	1.22E+02	1.99E+00
Steel, chromium steel 18/8 {GLO}| market for	Cut-off, U	2.16E+01	2.73E+02	7.63E+00
Sheet rolling, chromium steel {GLO}| market for	Cut-off, U	2.73E+00	4.02E+01	1.87E+00

Annex II Table 10. Environmental assessment during the manufacturing stage for Hot PCM container DHW

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO_{2eq}	MJ deprived	m3 world eq
Total	1.72E+02	2.81E+03	4.46E+01
SU-58 PCM	3.51E+01	1.05E+03	1.53E+01
Aluminium, wrought alloy {GLO}| market for	Cut-off, U	9.20E+01	9.74E+02	1.28E+01
Glass wool mat {GLO}| market for	Cut-off, U	5.77E+00	9.90E+01	2.51E+00
Polypropylene, granulate {RoW}| production	Cut-off, U	6.14E+00	2.45E+02	2.50E+00
Metal working, average for steel product manufacturing {GLO}| market for	Cut-off, U	8.66E+00	1.22E+02	1.99E+00
Steel, chromium steel 18/8 {GLO}| market for	Cut-off, U	2.16E+01	2.73E+02	7.63E+00
Sheet rolling, chromium steel {GLO}| market for	Cut-off, U	2.73E+00	4.02E+01	1.87E+00

Annex II Table 11. Environmental assessment during manufacturing stage for control unit

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO$_{2eq}$	MJ deprived	m3 world eq
Total	4.83E+02	7.08E+03	3.52E+02
Steel, chromium steel 18/8, hot rolled {GLO}| market for	Cut-off, U	2.70E+02	3.44E+03	1.09E+02
Sheet rolling, chromium steel {GLO}| market for	Cut-off, U	3.24E+01	4.76E+02	2.22E+01
Cable, unspecified {GLO}| market for	Cut-off, U	1.73E+02	2.95E+03	2.07E+02
Polyvinylchloride, emulsion polymerised {RER}| polyvinylchloride production, emulsion polymerisation	Cut-off, U	7.67E+00	2.23E+02	1.37E+01

Annex II Table 12. Environmental assessment during manufacturing stage for the two 42W pumps and other two 56W pumps

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO$_{2eq}$	MJ deprived	m^3 world eq
Total	2.09E+01	2.72E+02	1.09E+01
Pump, 40W {GLO}| market for	Cut-off, U	8.97E+00	1.16E+02	4.69E+00
Pump, 40W {GLO}| market for	Cut-off, U	1.20E+01	1.55E+02	6.25E+00

Annex II Table 13. Environmental assessment during manufacturing stage for the metallic container

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO$_{2eq}$	MJ deprived	m^3 world eq
Total	5.42E+03	7.49E+04	2.00E+03
Steel, chromium steel 18/8 {GLO}| market for	Cut-off, U	3.26E+03	4.11E+04	1.15E+03
Polyvinylchloride, suspension polymerised {GLO}| market for	Cut-off, U	2.69E+02	6.94E+03	2.02E+02
Steel, chromium steel 18/8 {GLO}| market for	Cut-off, U	9.78E+01	1.23E+03	3.45E+01
Sheet rolling, chromium steel {GLO}| market for	Cut-off, U	4.25E+02	6.24E+03	2.91E+02
Metal working, average for steel product manufacturing {GLO}| market for	Cut-off, U	1.35E+03	1.90E+04	3.09E+02
Steel, chromium steel 18/8 {GLO}| market for	Cut-off, U	2.16E+01	2.73E+02	7.63E+00
Sheet rolling, chromium steel {GLO}| market for	Cut-off, U	2.73E+00	4.02E+01	1.87E+00

Annex II Table 14. Environmental assessment during manufacturing stage for BESS

Impact category	Climate change, long term	Fossil and nuclear energy use	Water scarcity
Unit	kg CO$_{2eq}$	MJ deprived	m^3 world eq
Hybrid solar inverter	1.41E+02	2.20E+03	5.76E+01
Li-on Battery cell	1.35E+03	2.53E+04	5.09E+03

Environmental assessment of MiniStor system operation

All the LCA outcomes regarding the replication sites and the major impact categories are illustrated in the following figures.
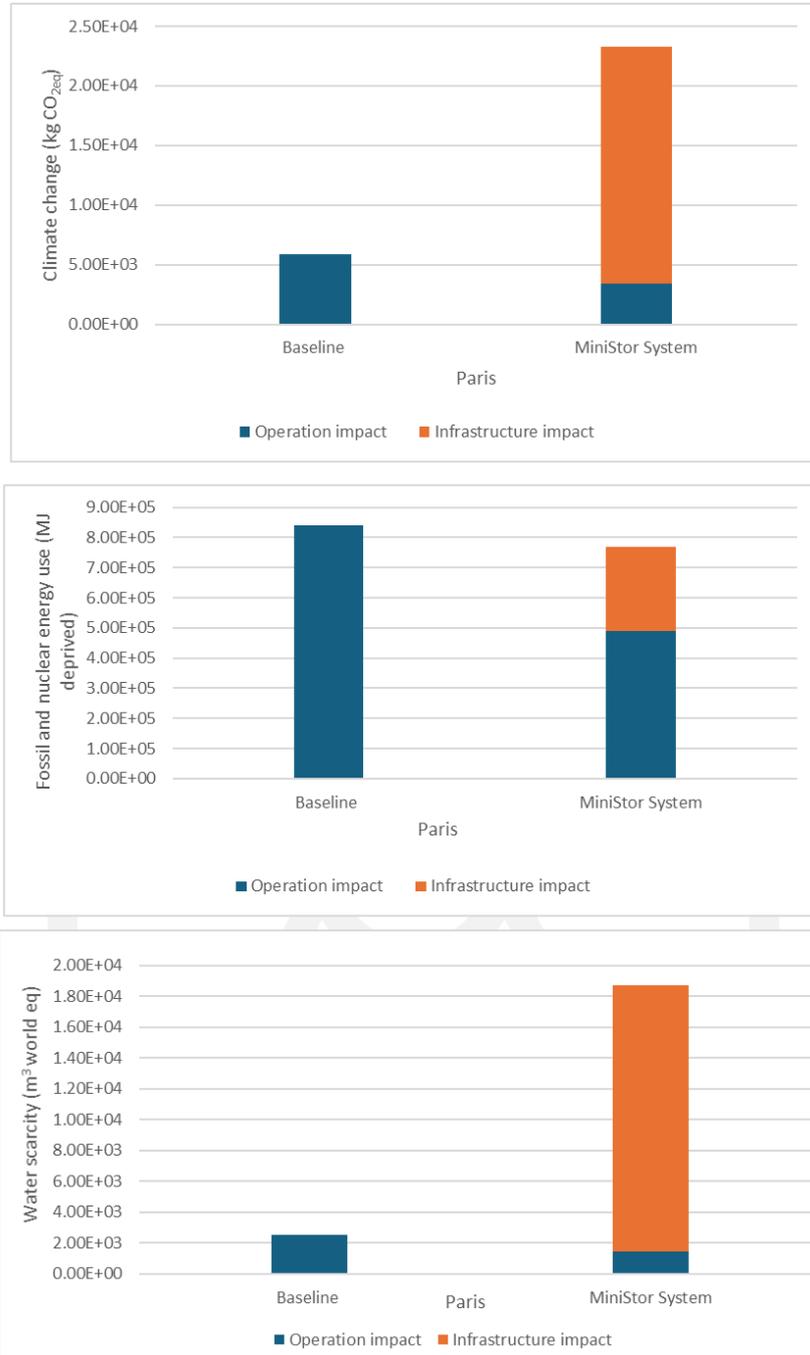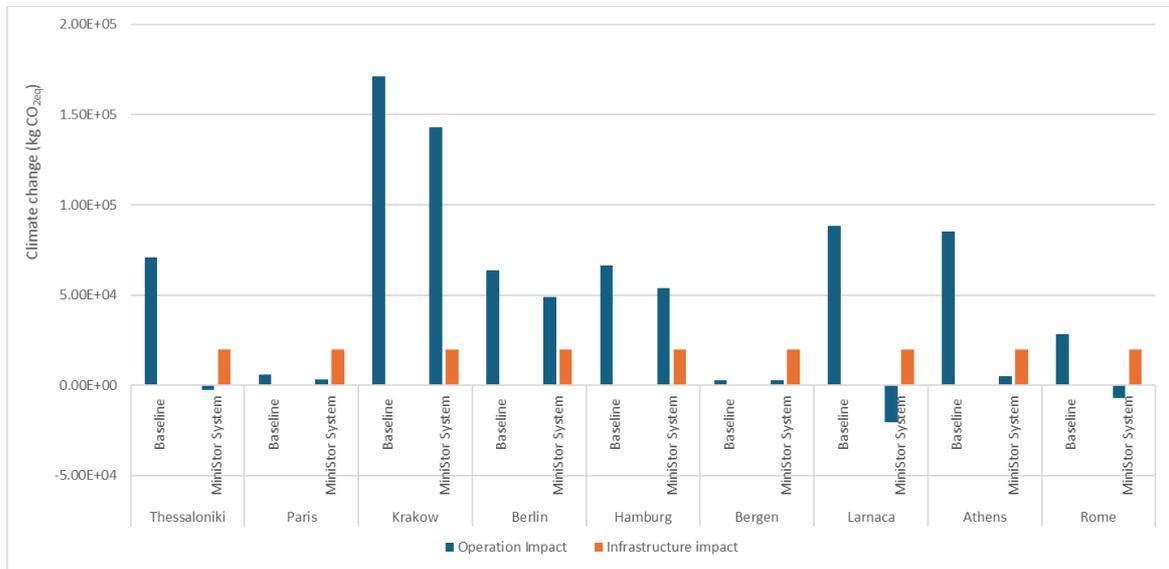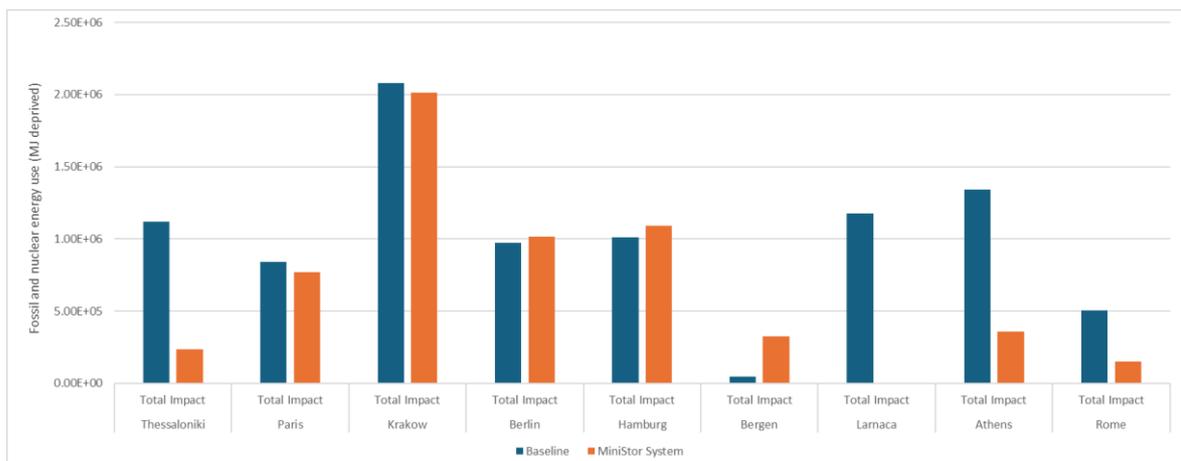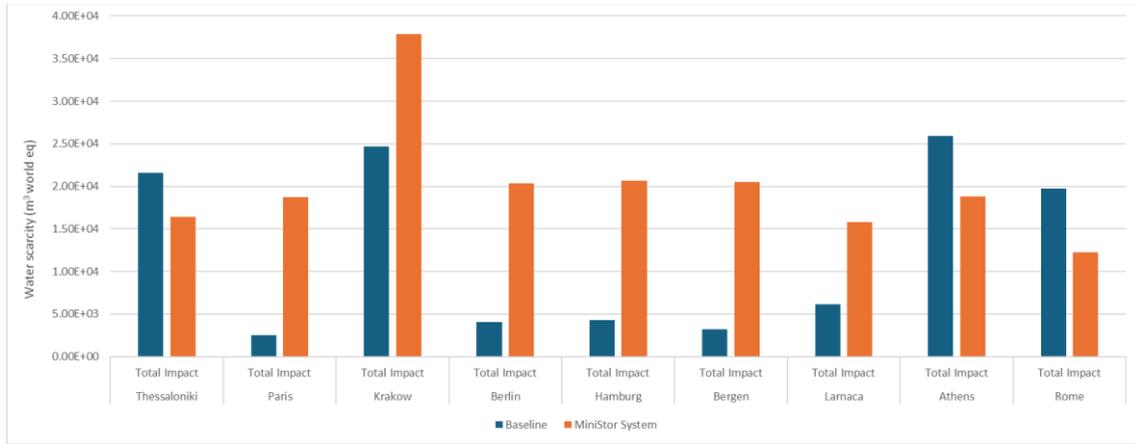

Annex II Figure 1. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Paris replication site during the lifetime
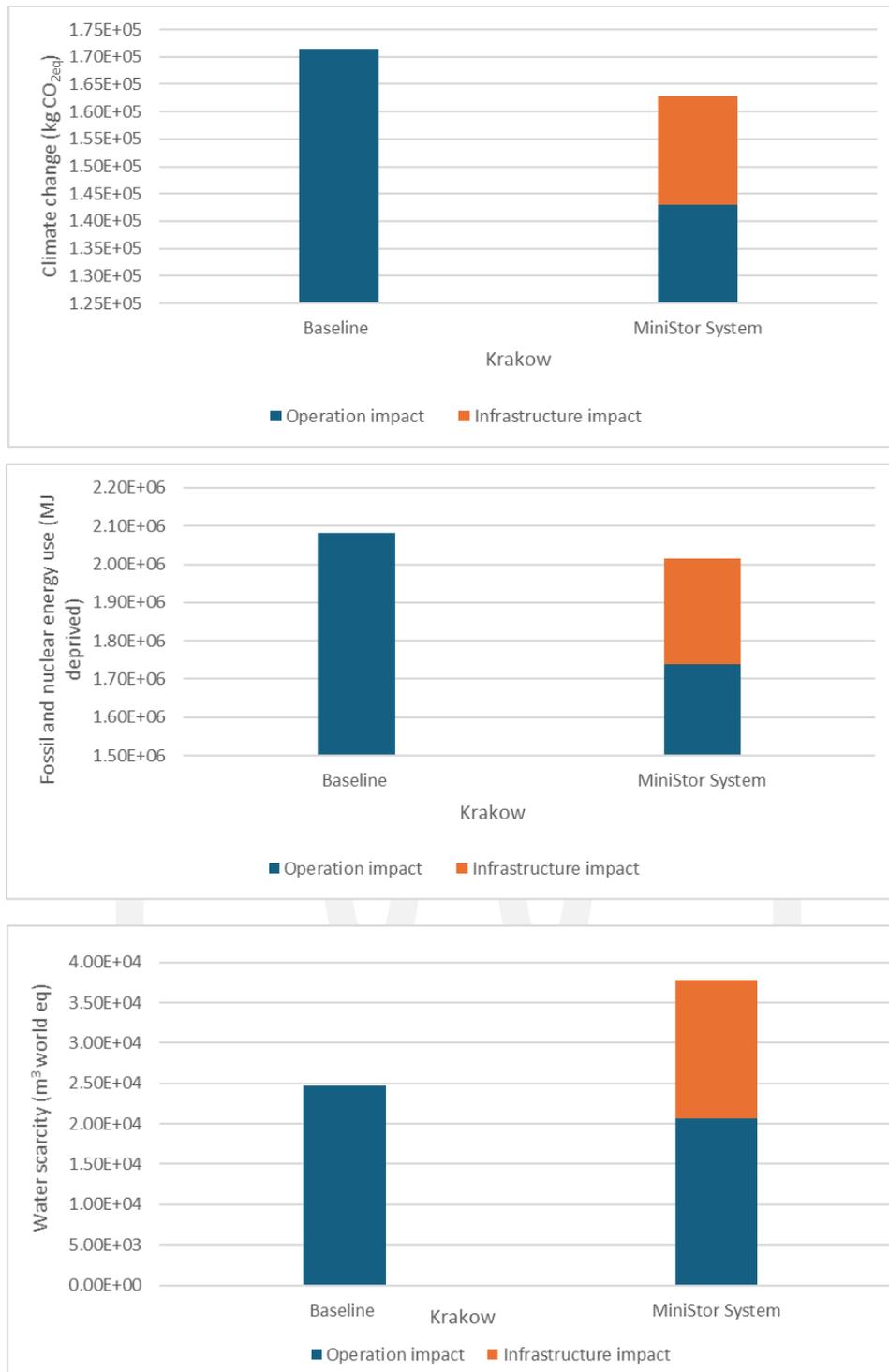
Annex II Figure 2. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Krakow replication site during the lifetime
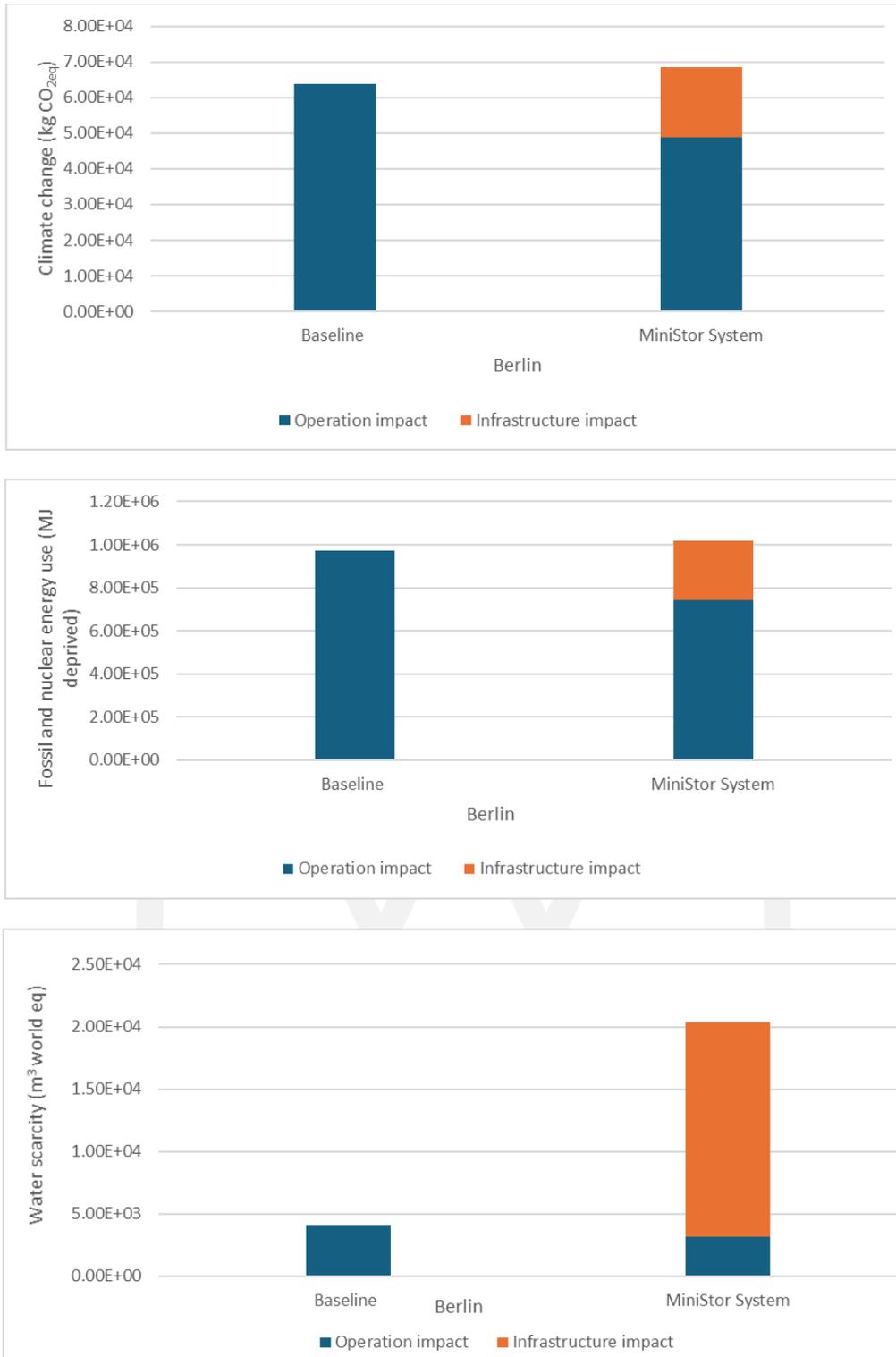
Annex II Figure 3. Comparison of MiniStor system major impact categories, climate change (kg CO$_{2eq}$), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Berlin replication site during the lifetime
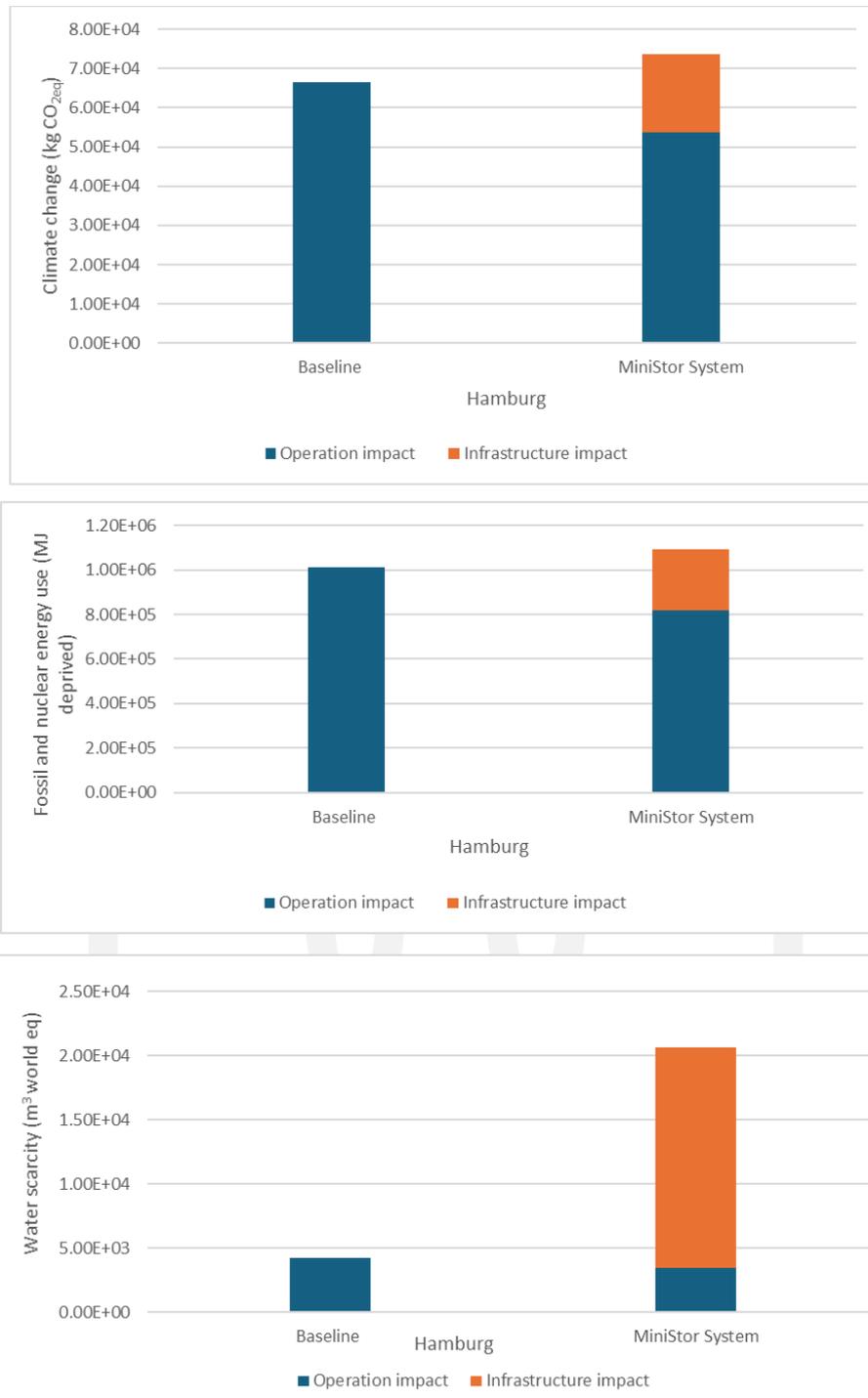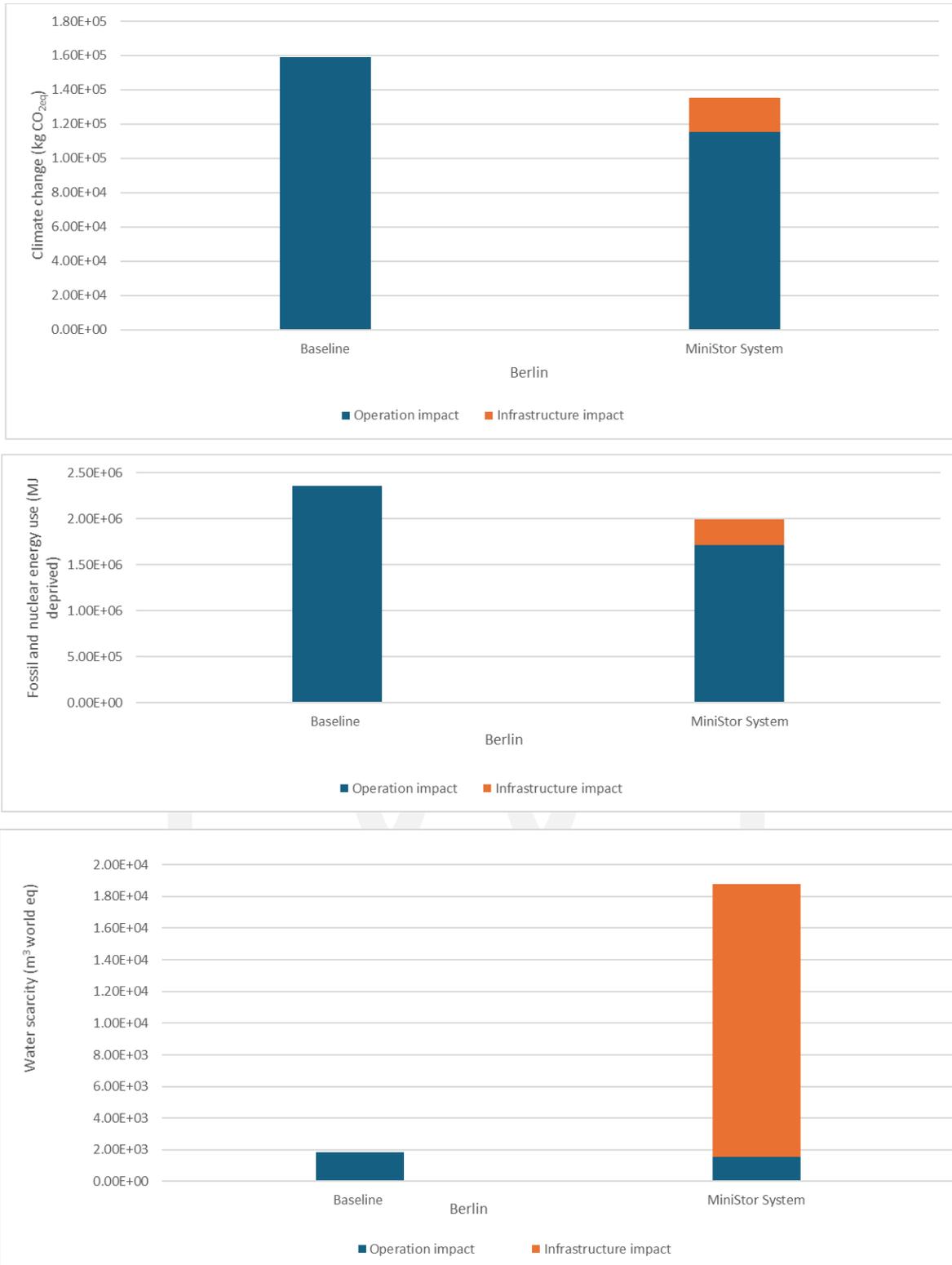
Annex II Figure 4. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Hamburg replication site during the lifetime
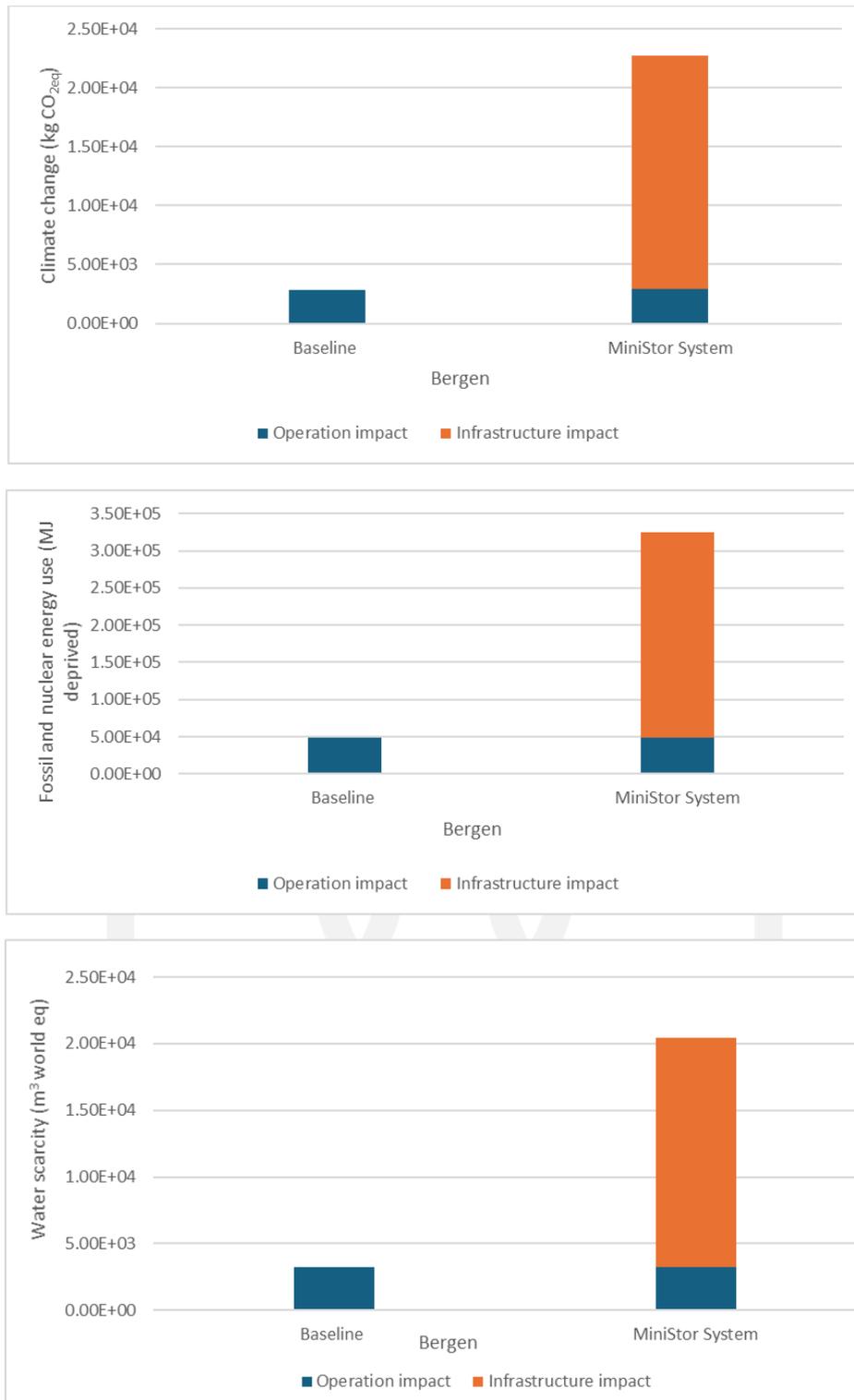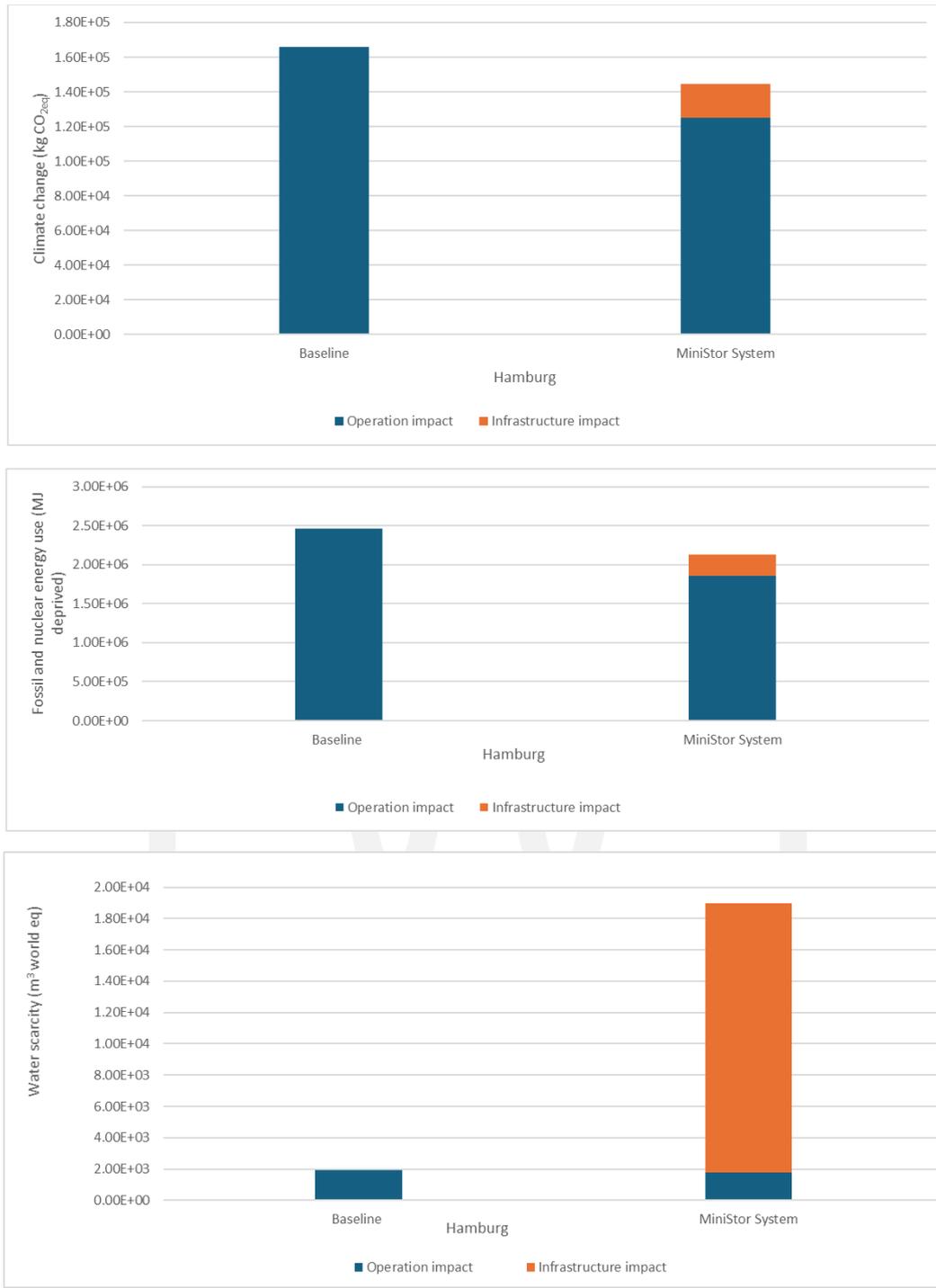
Annex II Figure 5. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Bergen replication site during the lifetime
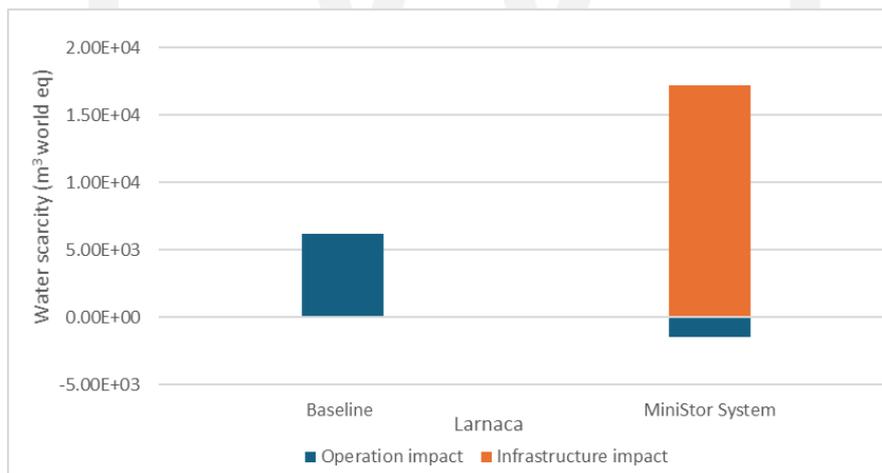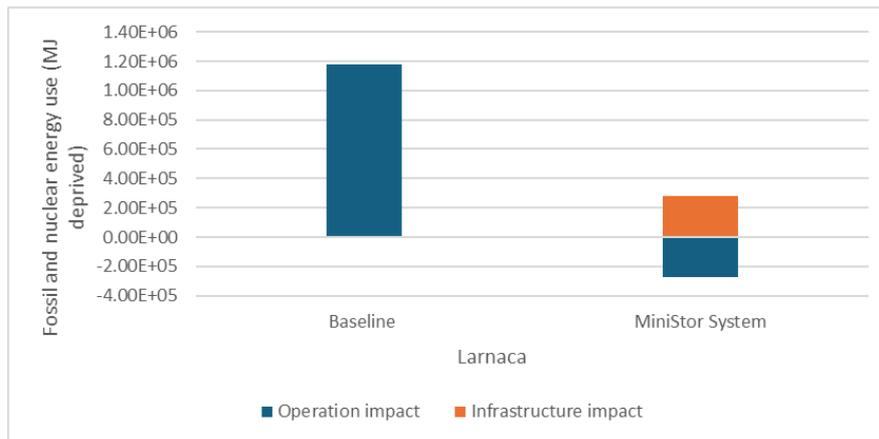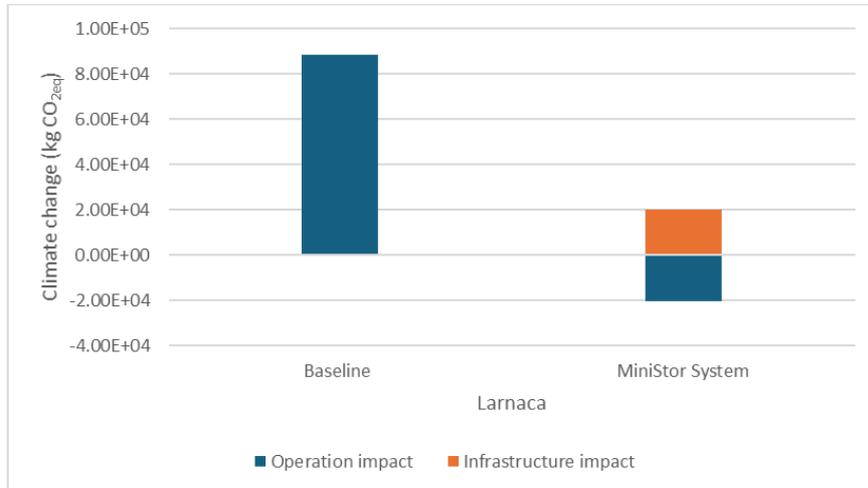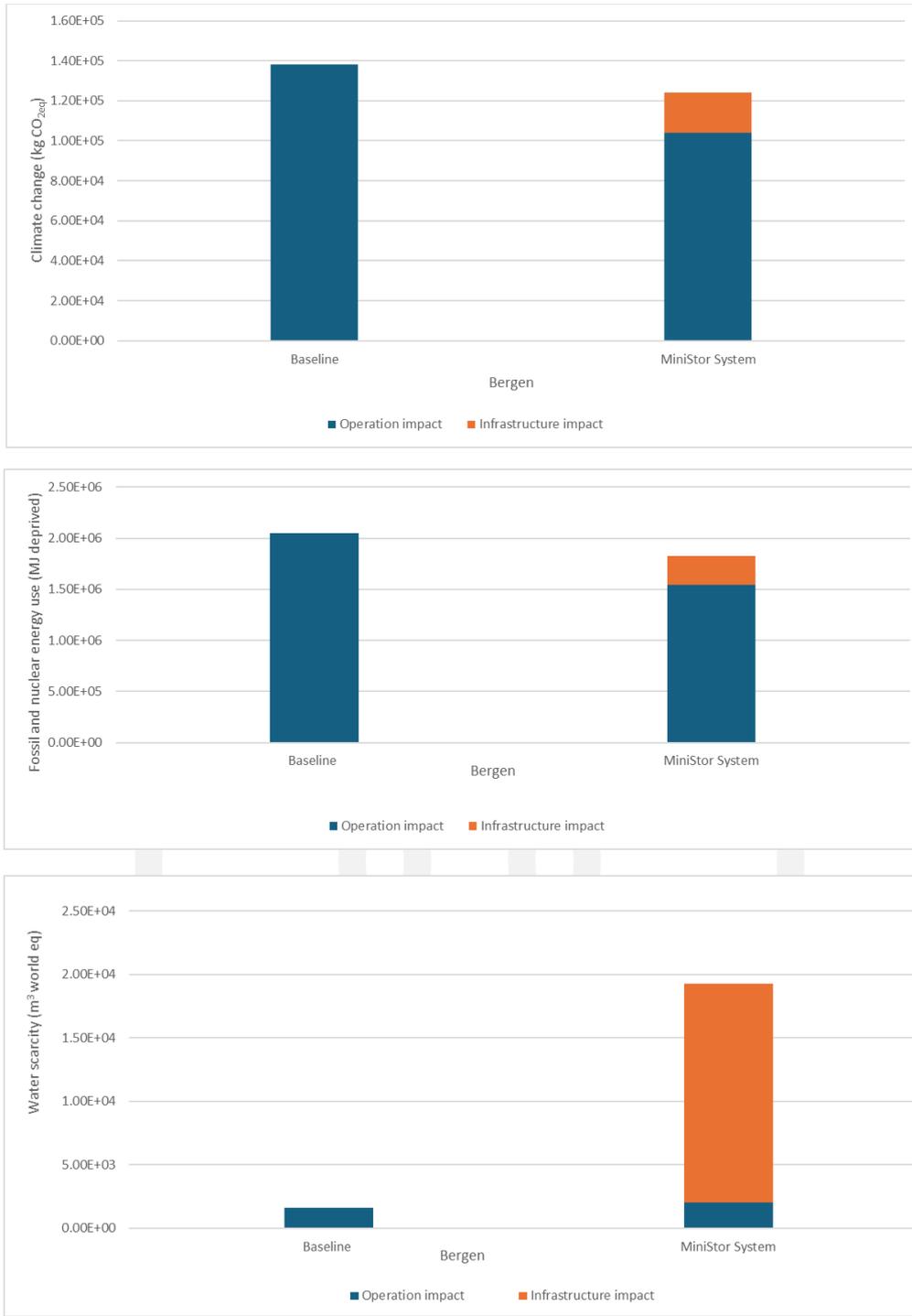
Annex II Figure 6. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Larnaca replication site during the lifetime
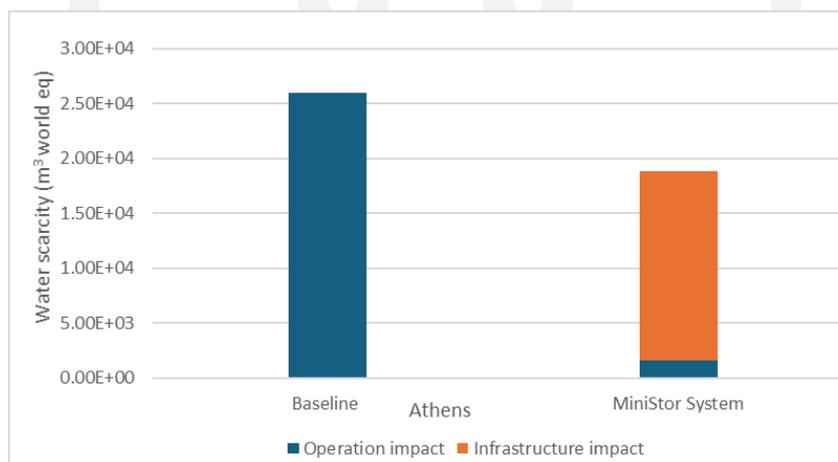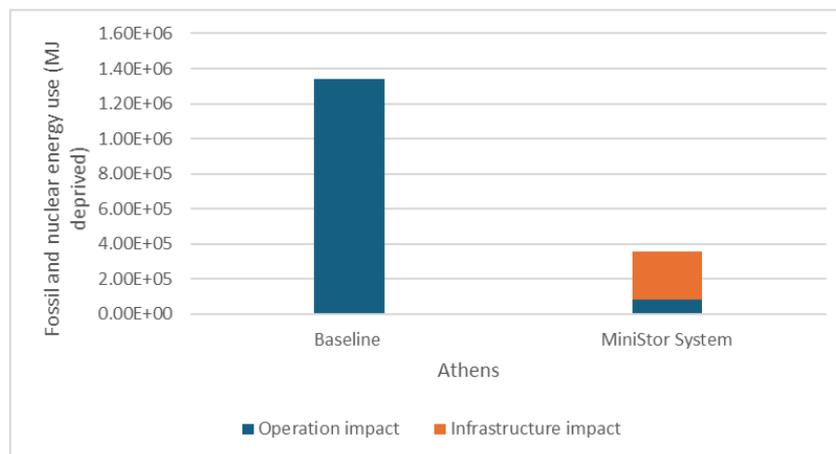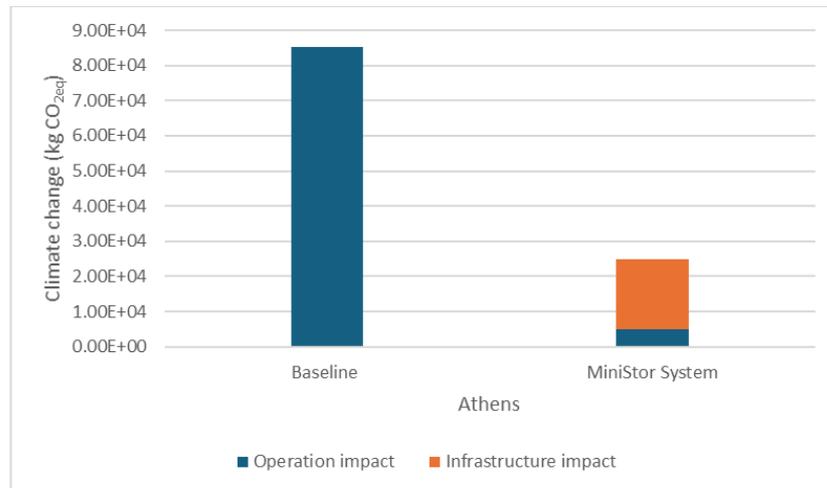
Annex II Figure 7. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Athens replication site during the lifetime
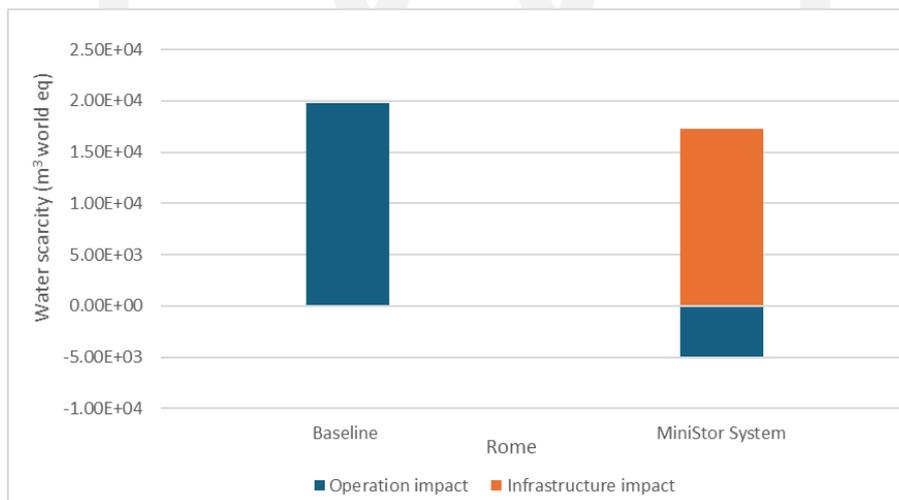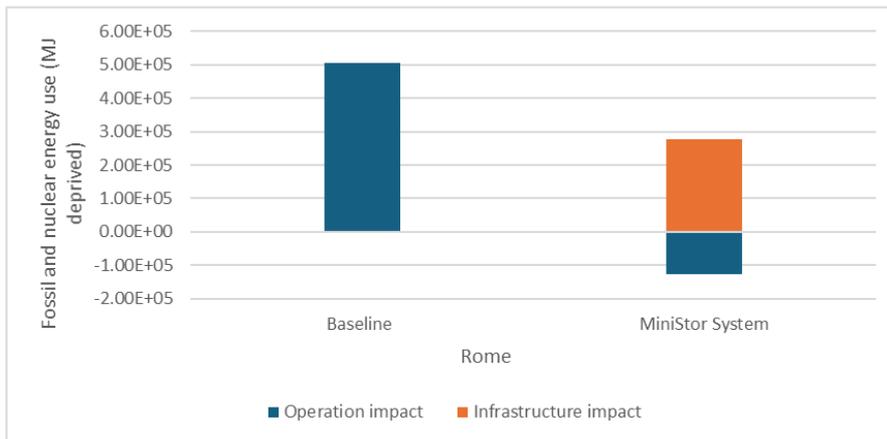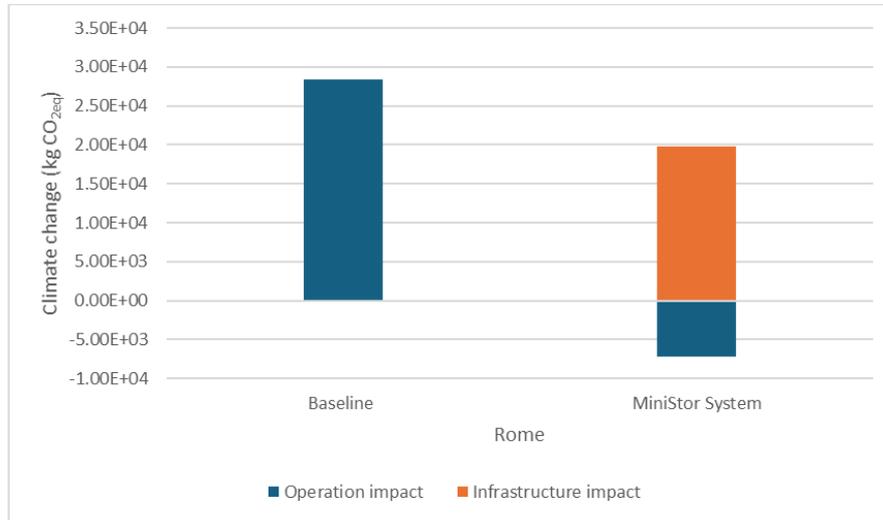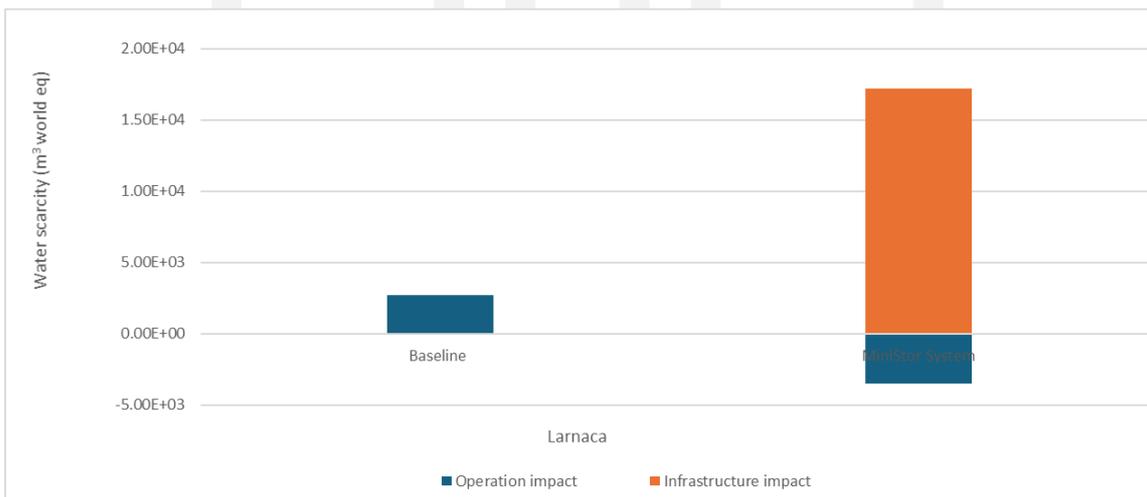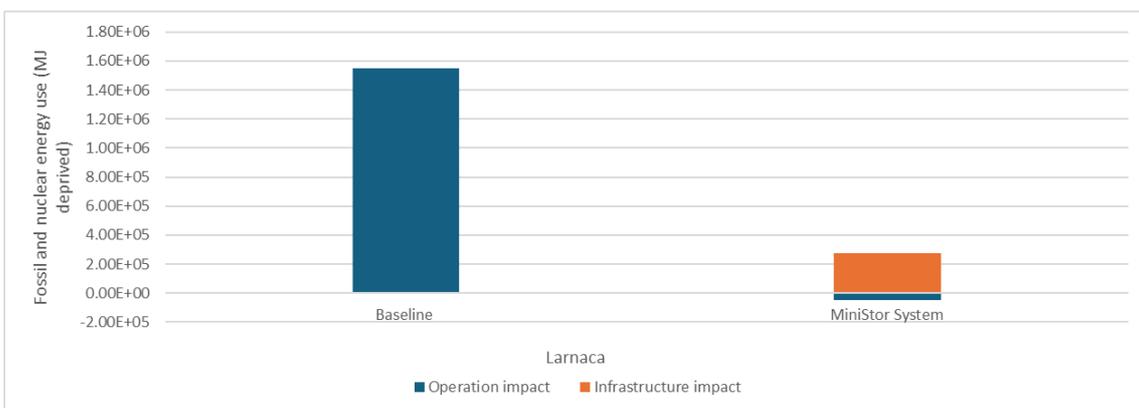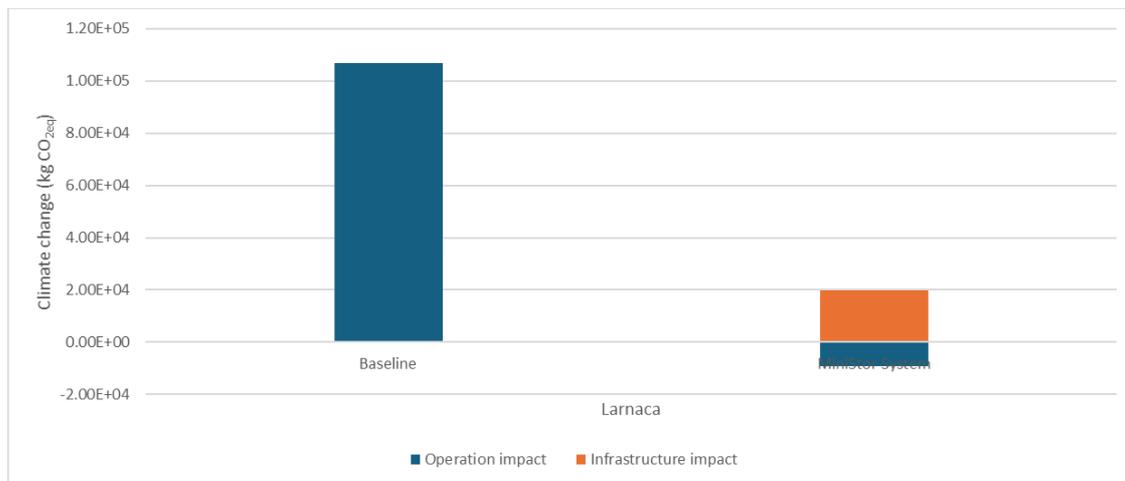
Annex II Figure 8. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Rome replication site during the lifetime

Annex II Figure 9. Comparison of the total impact of climate change (kg CO2eq), operation and infrastructure stage separately, in case of the baseline scenario and in case of MiniStor for the demo site and replication sites during the lifetime.

Annex II Figure 10. Comparison of the impact of Fossil and nuclear energy use (MJ deprived) in case of the baseline scenario and in case of MiniStor for the demo site and replication sites during the lifetime.

Annex II Figure 11. Comparison of the impact of Water scarcity (m^3 world eq) in case of the baseline scenario and in case of MiniStor for the demo site and replication sites during the lifetime.
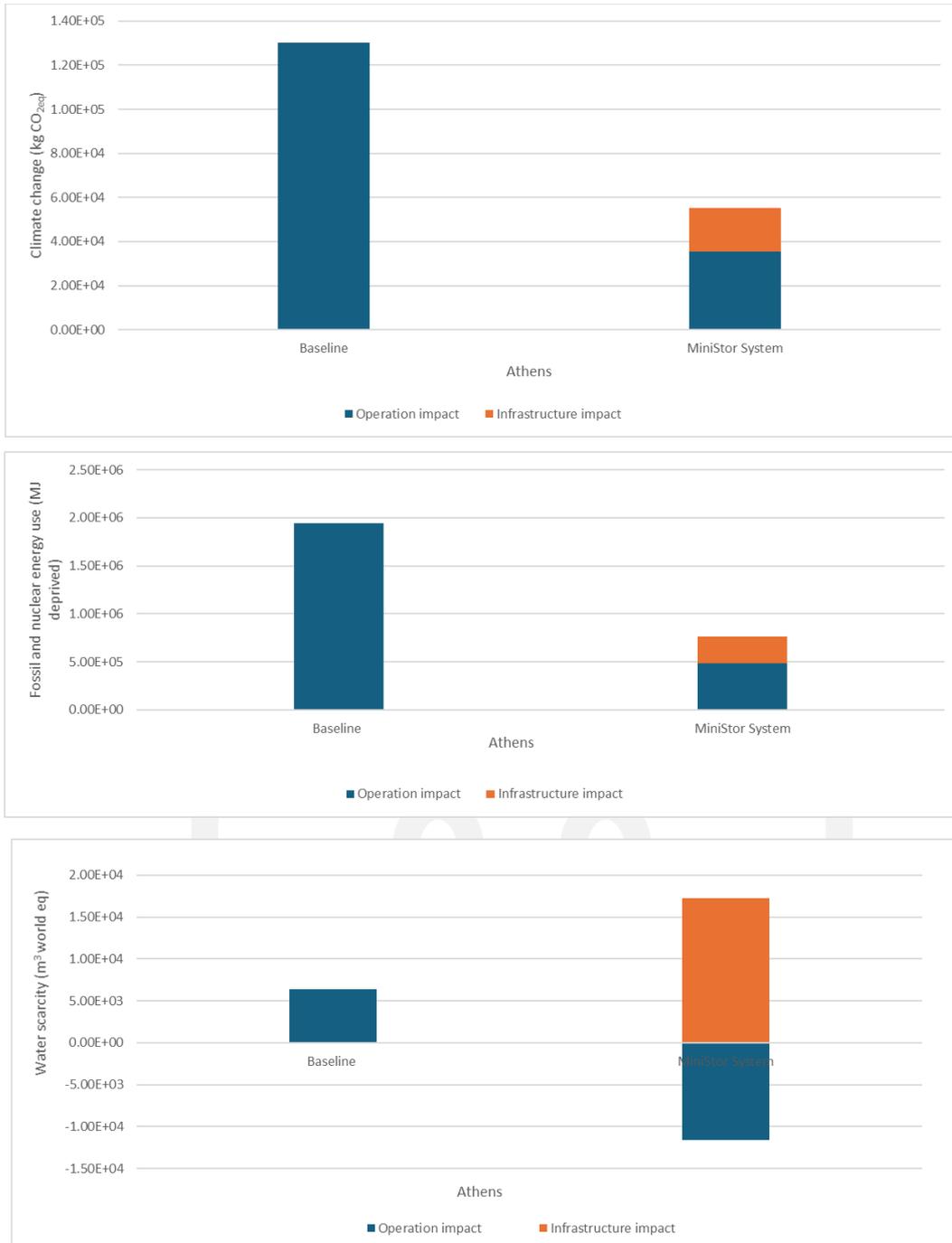
Scenario 2

Annex II Figure 12. Comparison of MiniStor system major impact categories, climate change (kg CO$_{2eq}$), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Paris replication site during the lifetime regarding 2nd scenario
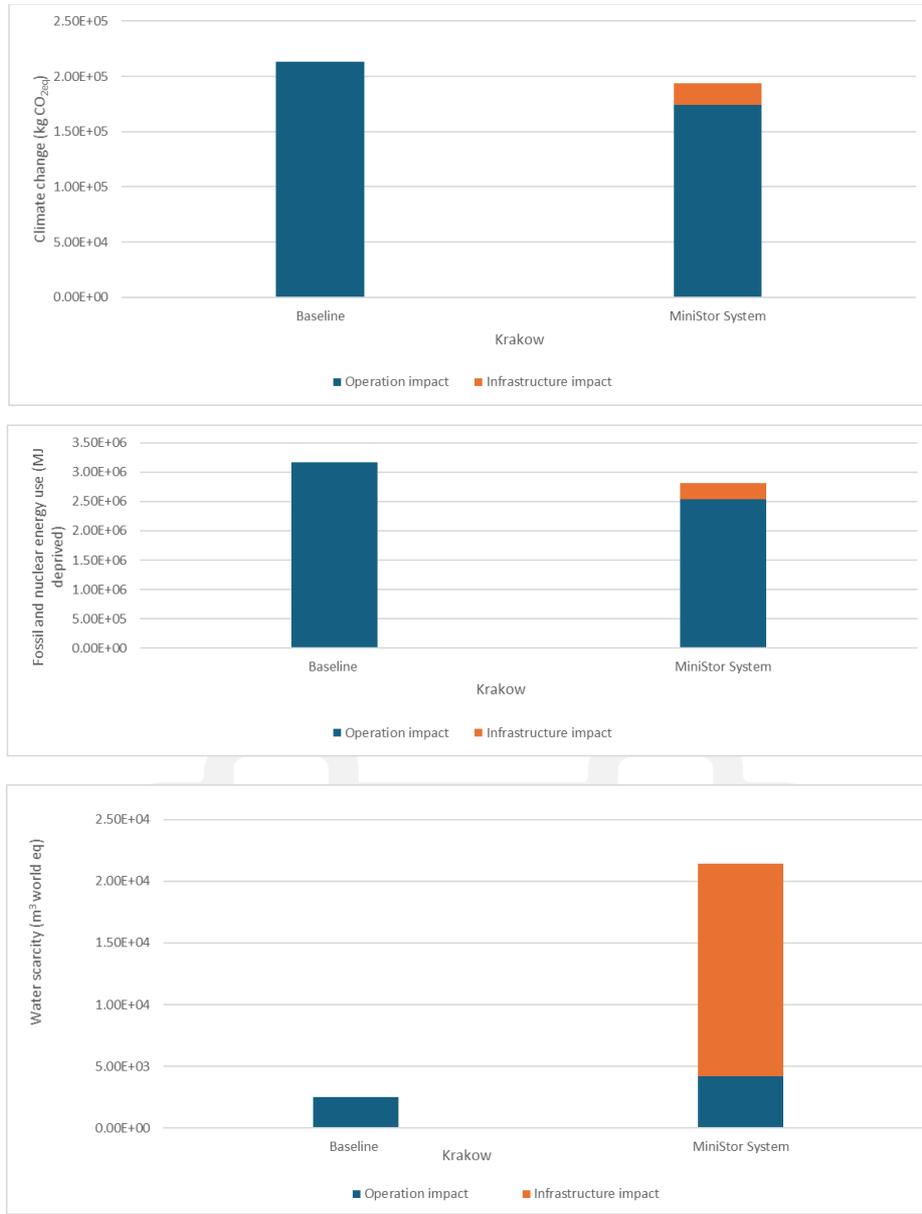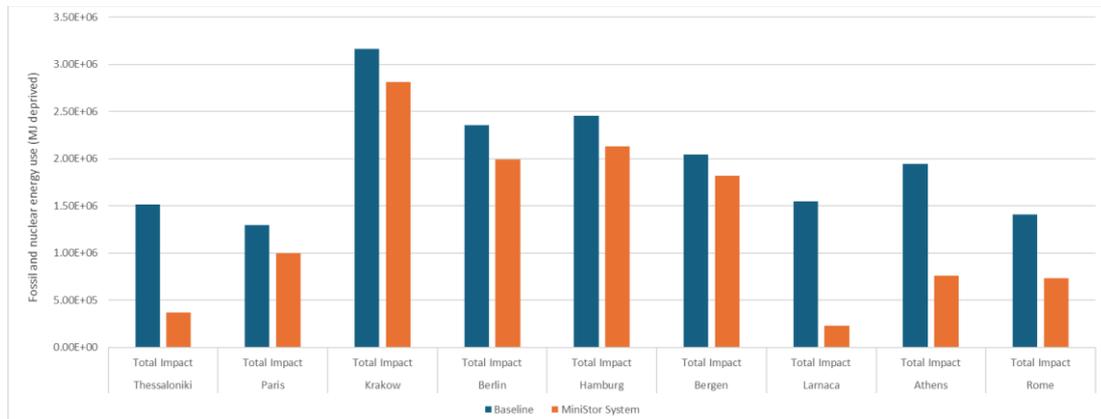
Annex II Figure 13. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Krakow replication site during the lifetime regarding 2nd scenario

Annex II Figure 14. Comparison of MiniStor system major impact categories, climate change (kg CO$_{2eq}$), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Berlin replication site during the lifetime regarding 2nd scenario
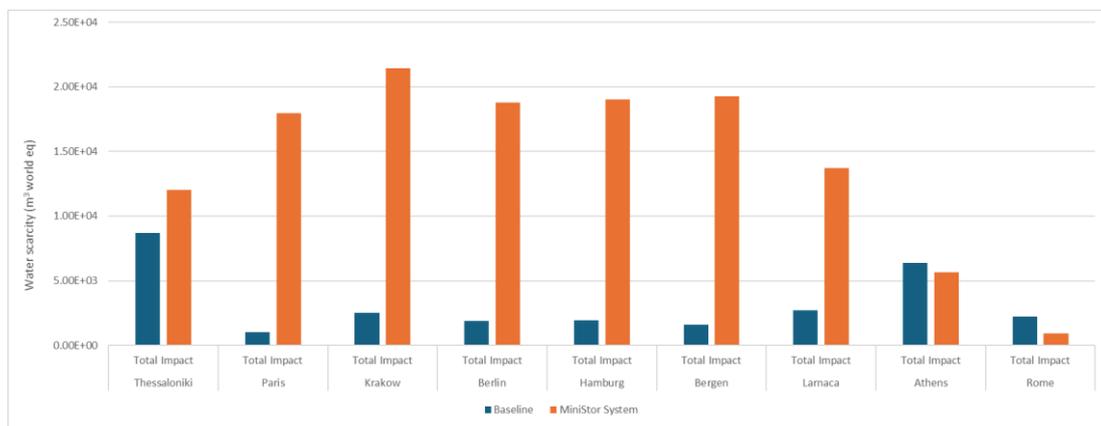
Annex II Figure 15. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Hamburg replication site during the lifetime regarding 2nd scenario

Annex II Figure 16. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Bergen replication site during the lifetime regarding 2nd scenario

Annex II Figure 17. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Larnaca replication site during the lifetime regarding 2nd scenario
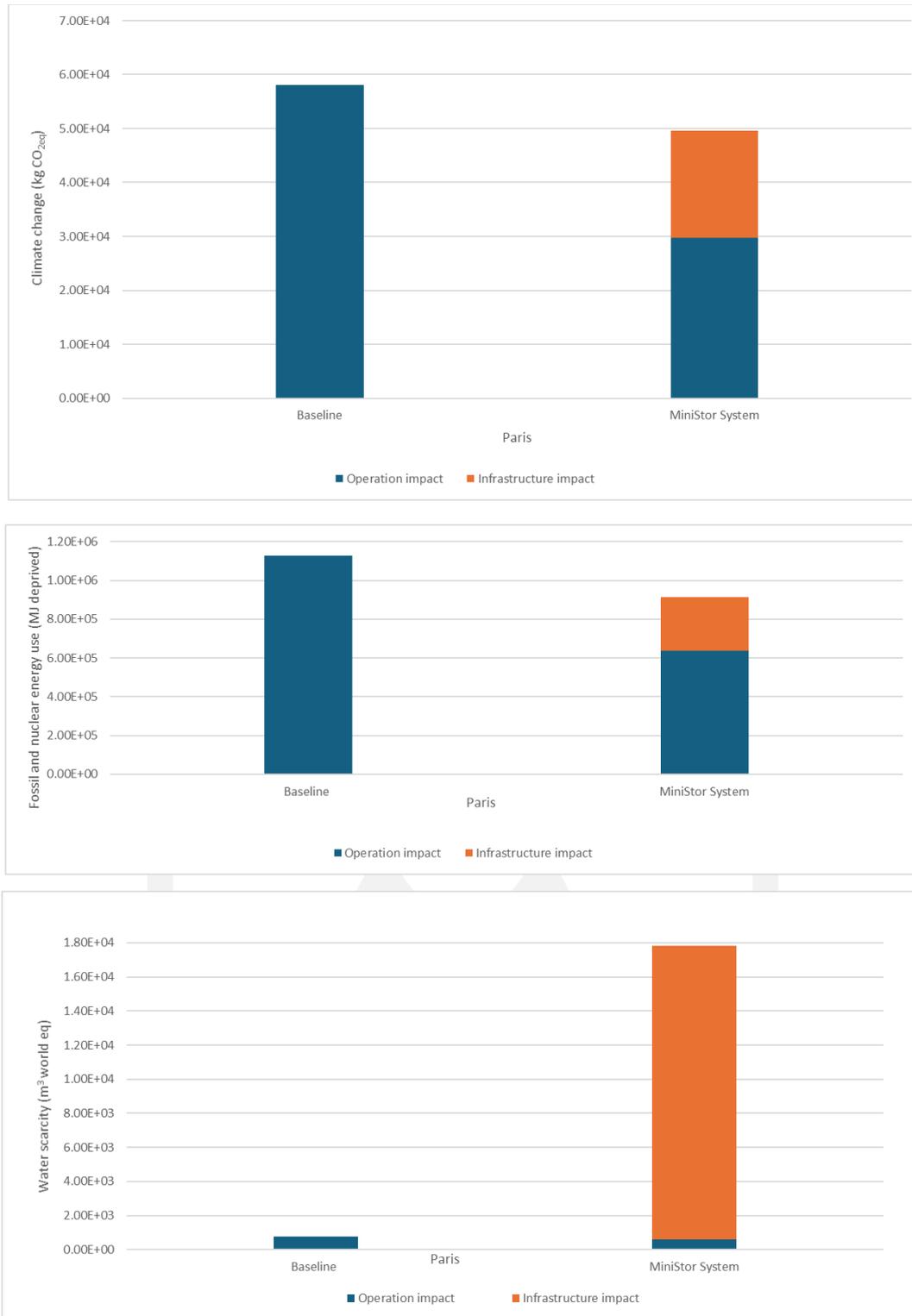
Annex II Figure 18. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Athens replication site during the lifetime regarding 2nd scenario

Annex II Figure 19. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Rome replication site during the lifetime regarding 2nd scenario
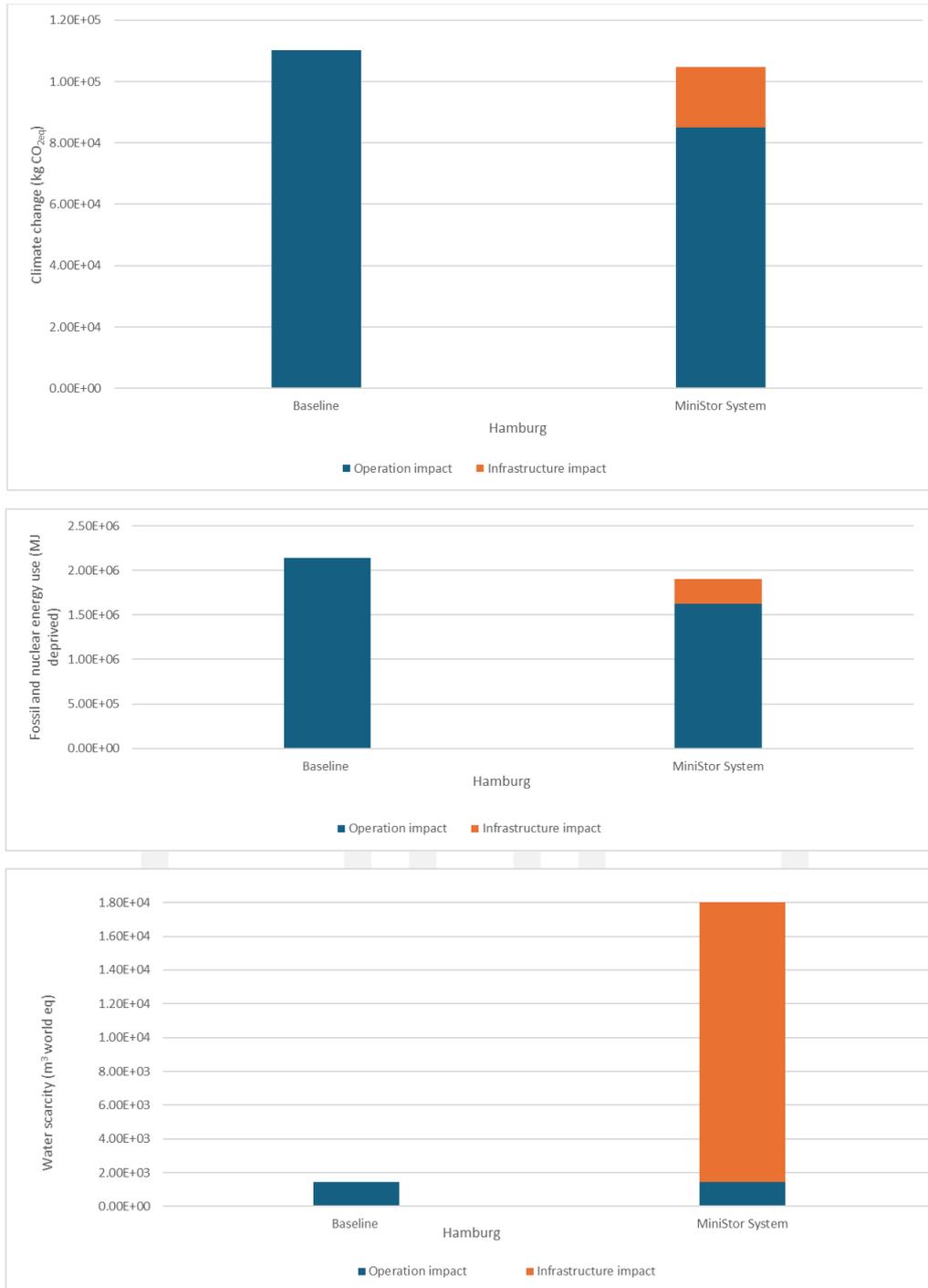
Annex II Figure 20. Comparison of the impact of Fossil and nuclear energy use (MJ deprived) in case of the baseline scenario and in case of MiniStor for the demo site and replication sites during the lifetime regarding 2nd scenario

Annex II Figure 21. Comparison of the impact of Water scarcity (m^3 world eq) in case of the baseline scenario and in case of MiniStor for the demo site and replication sites during the lifetime regarding 2nd scenario
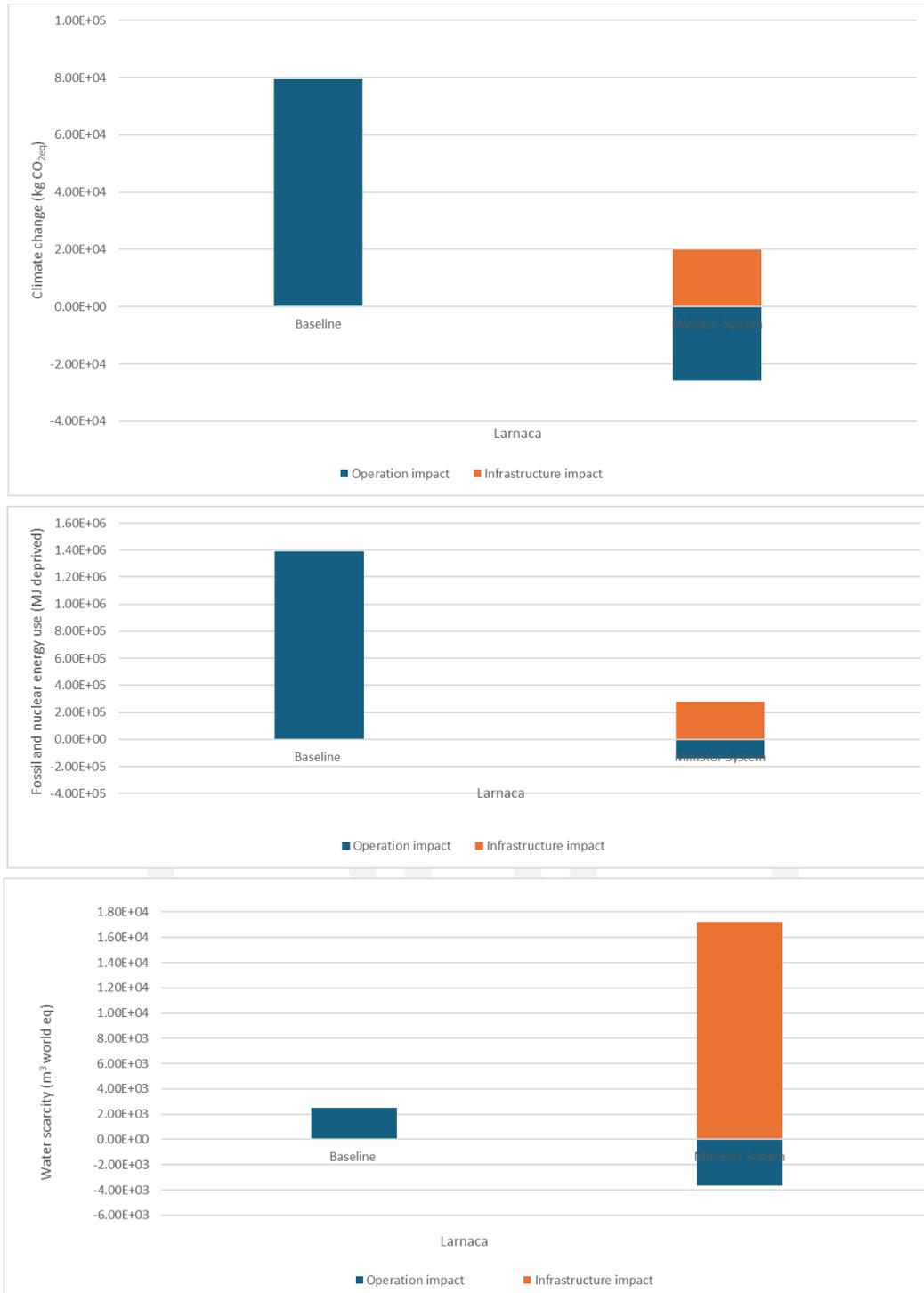
Scenario 3

Annex II Figure 22. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Paris replication site during the lifetime regarding 3rd scenario
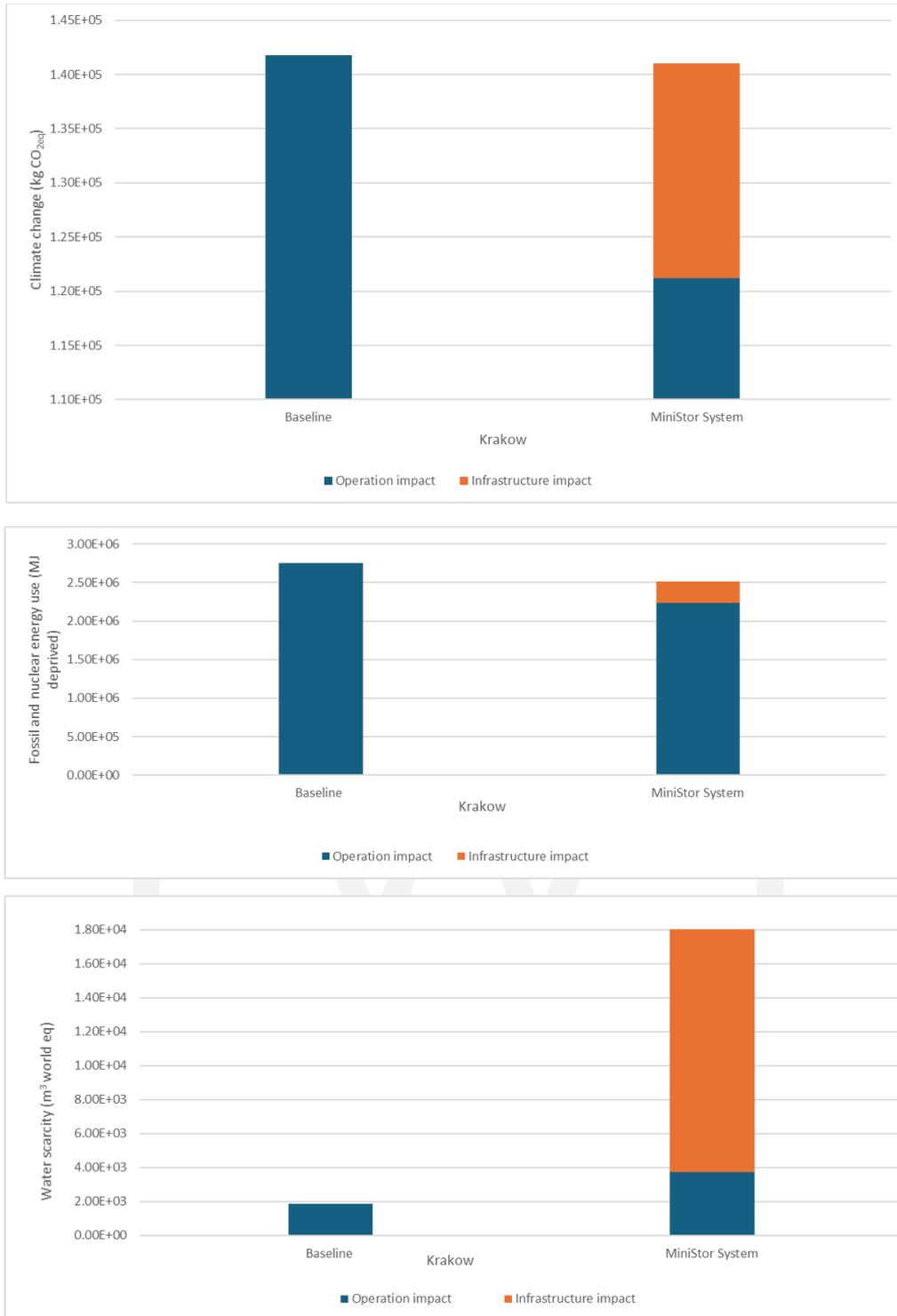
Annex II Figure 23. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Krakow replication site during the lifetime regarding 3rd scenario

Annex II Figure 24. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Berlin replication site during the lifetime regarding 3rd scenario
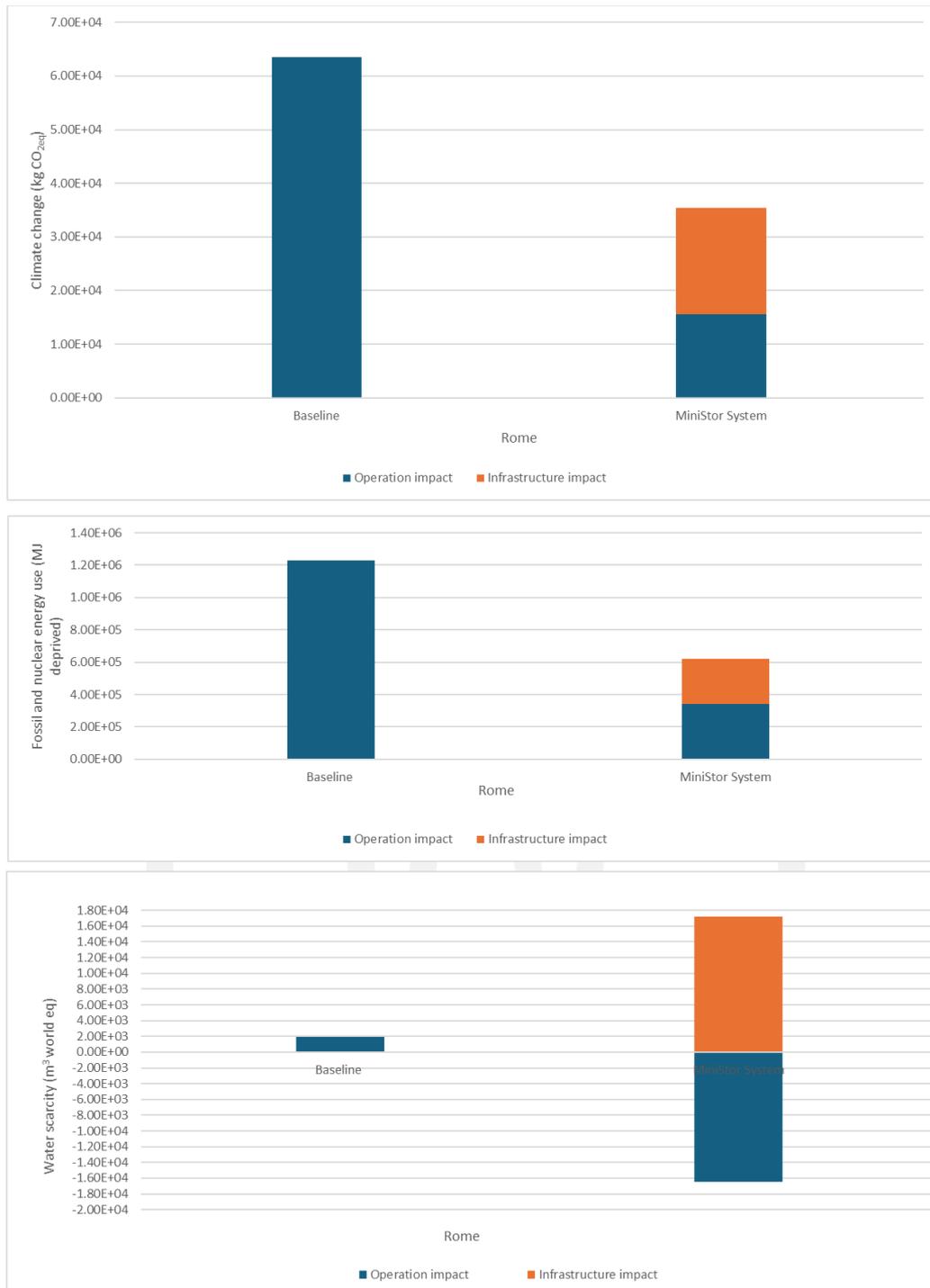
Annex II Figure 25. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Hamburg replication site during the lifetime regarding 3rd scenario
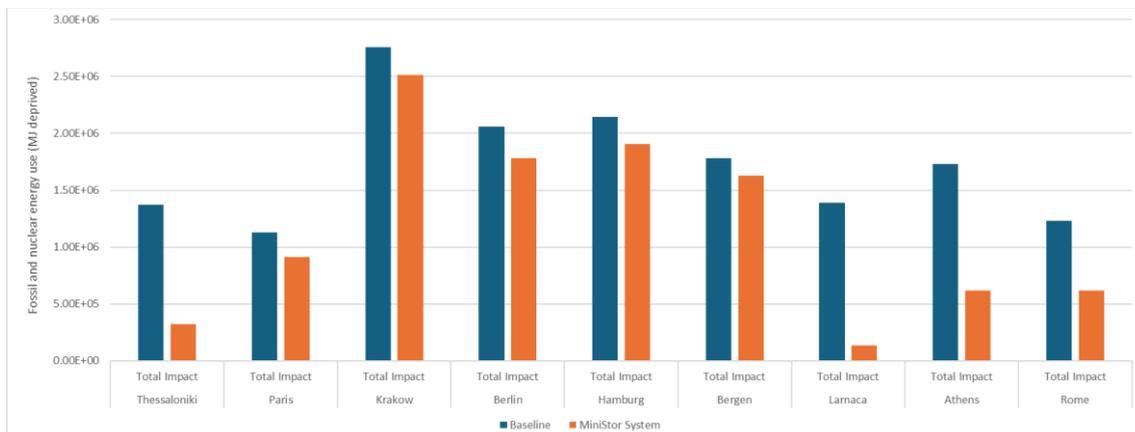
Annex II Figure 26. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Bergen replication site during the lifetime regarding 3rd scenario

Annex II Figure 27. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Larnaca replication site during the lifetime regarding 3rd scenario
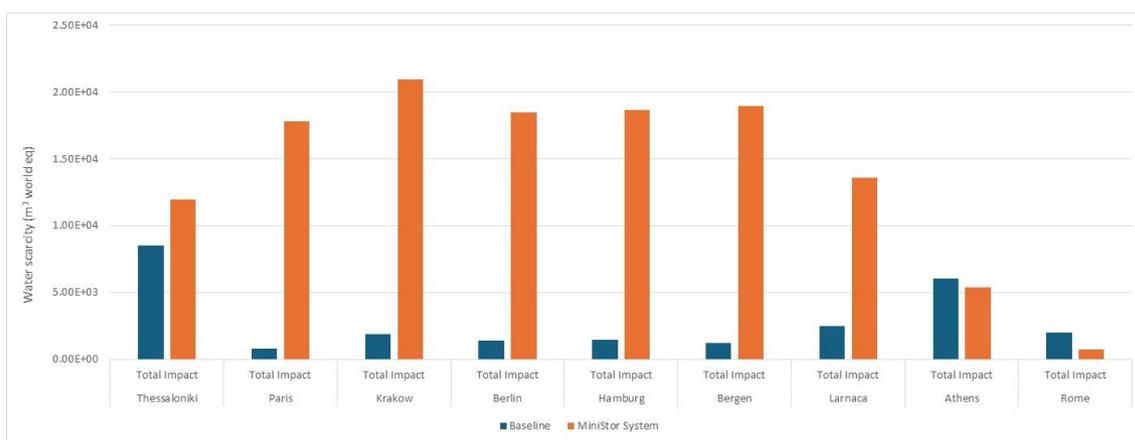
Annex II Figure 28. Comparison of MiniStor system major impact categories, climate change (kg CO$_{2eq}$), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Athens replication site during the lifetime regarding 3rd scenario

Annex II Figure 29. Comparison of MiniStor system major impact categories, climate change (kg CO_{2eq}), fossil and nuclear energy use (MJ derived) and water scarcity (m^3 world eq) with Baseline according to IMPACT World+ Midpoint V1.01 method in Rome replication site during the lifetime regarding 3rd scenario

Annex II Figure 30. Comparison of the impact of Fossil and nuclear energy use (MJ deprived) in case of the baseline scenario and in case of MiniStor for the demo site and replication sites during the lifetime regarding 3rd scenario

Annex II Figure 31. Comparison of the impact of Water scarcity (m^3 world eq) in case of the baseline scenario and in case of MiniStor for the demo site and replication sites during the lifetime regarding 3rd scenario

LCC of MiniStor system
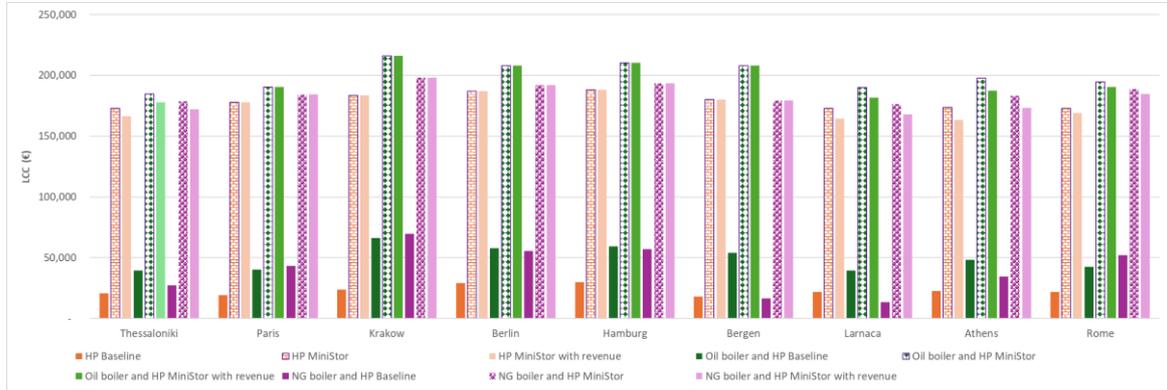
Annex II Figure 32. Comparison of LCC (€) and LCC (€) with revenue included for each scenario (HP: orange, oil boiler and HP: green and NG boiler and HP: purple) in baseline case and in the MiniStor system case for Thessaloniki demo site and the replication sites over the lifetime