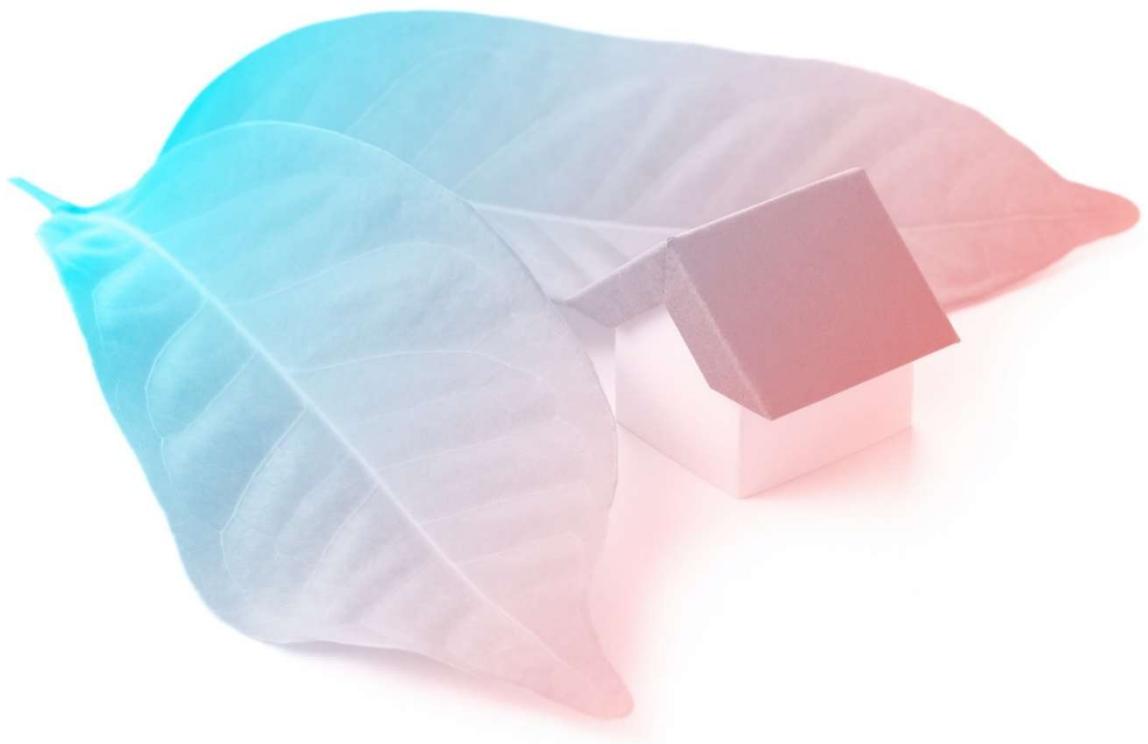# D6.7 Feasibility analysis for installation replication across Europe

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D6.7 Feasibility analysis for installation replication across Europe

Summary
Deliverable "D6.7 Feasibility Analysis for Installation Replication across Europe", provides a comprehensive evaluation of the MiniStor system's installation procedures, focusing on its technical potential for replication across the EU and Mission Innovation countries with harsh climatic conditions. It assesses the entire installation process, identifies legislative and logistical challenges, and presents a methodology for evaluation the systems technical potential for replication. Key findings indicate that while the MiniStor system can significantly contribute to meeting heating and cooling demands—reaching MiniStor's target of 50% renewable energy source (RES) utilization—the need for auxiliary grid supplied electricity is necessary in regions with low solar radiation and/or harsh winters. The system also shows potential for generating surplus electricity during summer that can be utilized for revenue generation. The replication methodology is focused only on residential buildings without considering district and city level installations due to legislation restrictions regarding the amount of ammonia that can be used in MiniStor. The document emphasizes the importance of legislative compliance and careful planning, offering practical recommendations to support successful replication and broader adoption of the MiniStor system to reduce energy consumption and sustainability across Europe.

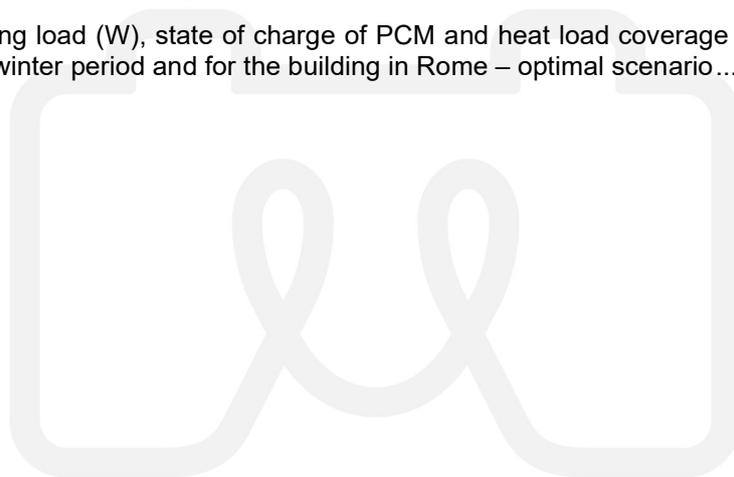| Deliverable Number		Work Package	
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Table of Contents

List of Tables

List of Images

1. Introduction

1.1 Scope and objective

"D6.7 Feasibility Analysis for Installation Replication across Europe" presents a detailed analysis and evaluation of the MiniStor system's installation procedures, with an emphasis on their technical potential for replication across the European Union (EU) and Mission Innovation countries that experience harsh climatic conditions.

The primary objective of this feasibility analysis is to assess the entire installation process, from pre-assembly and shipment to installation and commissioning, to identify any difficulties encountered and highlight their implications for broader application. The aim is to generalize the experiences from the initial installation sites and evaluate their technical replication potential at other buildings in various regions.

To achieve this, the document provides a comprehensive methodology that includes the selection of EU regions with harsh climatic conditions, legislative analysis regarding the use of ammonia, and an assessment of suitable building topologies.

Simulation results to assess the system's performance in different climatic areas are utilized based on the methodology described in D3.1 (Zisopoulos, 2023). The findings from this analysis provide valuable insights into the challenges and successes of the installation process and offer recommendations for future installations.

By drawing on these experiences, the deliverable presents a set of guidelines and recommendations that will facilitate the replication of the MiniStor system in other residential buildings. The information presented is used in the deliverables of Work Package 7 (WP7) to create robust business cases for the further exploitation of the Ministor system, ensuring its economic viability and scalability as presented in WP7.

Overall, this deliverable aims to pave the way for the successful replication and broader adoption of the MiniStor system, contributing to enhanced energy efficiency and sustainability across the EU and beyond. The insights and recommendations provided will be crucial for stakeholders looking to adopt and replicate this innovative technology in various regions, particularly those with challenging climatic conditions.

1.2 Structure and connections with other tasks

This deliverable is structured into four key sections as to systematically address the analysis and evaluation of the MiniStor system's installation procedures and replication potential. The structure is as follows:

- Chapter 2 reviews EU legislation regarding ammonia use in residential applications. It also provides details for the installation procedures and the challenges encountered during each phase of the installation process.
- Chapter 3 outlines the methodology for evaluating the system's technical replication potential, including selection of EU regions with harsh climatic conditions and representative building typologies.
- Chapter 4 presents the findings from the analysis, including the Ministor's average annual performance evaluation based on the initial operating strategy, as well as strategies to increase the systems annual performance along with potential barriers for the systems replication potential.
- Chapter 5 includes key insights from the analysis and provides recommendations for successful exploitation of the system.

This deliverable is closely connected with several other tasks within the MiniStor project to ensure a comprehensive and integrated approach to the feasibility analysis and replication potential. Key connections include "D2.3 Analysis of Relevant Legislation and Standards for System Operation", "D3.1 Initial dimensioning of the system according to general use typologies" that presents the simulation methodology for the performance of the Ministor system, "D6.3 Results from pre-pilot implementation and stakeholder training", "D6.4 Installation and commissioning report" that provide information on the steps taken and the problems associated in the various demos, and "WP7 - Business Case Development". The findings from WP2 are used to assess legal barriers and provide recommendations for the systems compliance and adaptation in different regions. The MiniStor model, developed in D3.1, is used for evaluating the system's performance for the technical potential under various climatic conditions. As part of WP6, this deliverable draws directly from the experiences and data collected during the initial installations of the MiniStor system. The detailed analysis of installation procedures and obstacles encountered is based on the practical insights gained from these activities. WP7 will utilize the information from this deliverable to develop robust business cases that support the economic viability and scalability of the MiniStor system. Furthermore, the methodology used for assessing the technical potential in various climatic conditions will be utilized in the forthcoming D7.3 to evaluate the systems life cycle cost and life cycle environmental impact. The recommendations and insights from the feasibility analysis will be integrated into the broader business strategy, ensuring that the system's adoption is both feasible and sustainable.

By leveraging the findings and methodologies from these interconnected tasks, this deliverable aims to provide a comprehensive analysis that facilitates the successful replication of the MiniStor system across diverse regions with harsh climatic conditions.

2. Legislative analysis and installation procedures

This chapter presents an analysis of the legislation regarding the use of ammonia in refrigeration systems, and the difficulties during the assembly, preparation, shipment, installation, and commissioning procedures for the pre-pilot site of Thessaloniki (as the first demo to be installed).

2.1   Summary on Ammonia Use legislation in the EU

Ammonia (NH_3) is a natural refrigerant[1] with favourable thermodynamic properties within a wide range of operating temperatures, low evaporation and condensation pressures and high latent heat capacity (Heinen & Hopman, 2024) which make it particularly suitable for use in Refrigeration and Air-conditioning systems.

In refrigeration applications its code name is R717, and its use has been mainly focused on industrial facilities related to food storage (ASHRAE, 2002, Eurammon, 2016). As a result of the phase out of hydrofluorocarbon (HFC) materials enforced by the F-gas regulation (EU) 2024/573 (European Parliament and Council of the European Union, 2024) in the EU, to reduce GHG emissions, it is now becoming more popular in low-charge applications also including residential installations (Zolcer Skačanovà et al., 2019).

It should be noted that EU is leading the effort in the wider use of R717. As of 2019 Europe accounted for more than 50% of low-charge ammonia system installations globally accounting for approximately 2,200 out of 4,000 systems (Birchby et al., 2022). Since ammonia has zero Global Warming Potential (GWP), zero Ozone Depletion Potential (ODP) and is biodegradable, it is

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[1] Despite the fact that ammonia is technically produced for use in refrigeration applications, it occurs in nature

considered as an environmentally/climate-friendly alternative that can replace the HFCs found in HVAC and refrigeration systems which have high GWP (Ferruci, 2024).

However, ammonia is also characterized by moderate flammability and a high level of toxicity (classification B2L). It has a strong distinctive odour which means that it can be easily detected (at just 3 mg/m^3), before reaching life-threatening levels (it is considered dangerous at concentration levels of greater than 1,750 mg/m^3) (Eurammon, 2016). In the EU, its use is regulated by European Standard series EN 378 which defines the required measures and guidelines for ensuring its safe use by setting (AREA, 2019):

- Concentration Limits: Part 1 of the EN 378 (CEN, 2020a) standard sets limits on the concentration of ammonia that can be used in refrigeration systems according to the access category of the occupied space that may be affected by a potential leak, the location classification of the refrigerating system, the type of the refrigeration system and the ammonia toxicity level. This is to ensure that the concentration is within safe levels to prevent health hazards.
- System Design: Part 2 of the Standard (CEN, 2016) sets specific design requirements for refrigeration systems using R717 in order to minimize the risk of leaks. This includes specifications for pipe materials, equipment layout, and emergency shut-off systems.
- Location Restrictions and Safety Equipment: EN 378-3 (CEN, 2020b) sets restrictions on where ammonia refrigeration systems can be installed and defines requirements for the machinery rooms and leak detection sensors as well as emergency ventilation systems, and personal protective equipment for workers handling ammonia. This is to mitigate the potential impact of leaks or accidents.
- Part 4 of the Standard (CEN, 2019) provides guidance on the maintenance and repair of the equipment, for the handling and storage of the refrigerant and its recycling and/or disposal.

The standard sets the requirements for HVAC systems and heat pumps using ammonia (and other refrigerants) to work in a safe manner; it sets the maximum permissible limit on refrigerant charge according to the access category of the space where the refrigerant might leak. A thorough description of the restrictions set out by EN 378 is provided in 'D2.3 - Analysis of relevant legislation and standards for system operation'.

Additionally, the following EU Directives regulate the use of ammonia as a refrigerant:

- The Pressure Equipment Directive (PED) 2014/68/EU (European Parliament and Council of the European Union, 2014) which sets essential safety requirements for pressure equipment, including refrigeration systems that use ammonia. It ensures that such equipment is designed, manufactured, and installed in a manner that prevents risks to human health and safety. It should be noted that the EN 378 Standard is also harmonized with the Pressure Equipment Directive (PED).

Furthermore, as R717 is a flammable substance, the following Directives and Standards are of interest (REAL, 2017):

- ATEX Directive 2014/34/EU: This directive governs equipment and protective systems intended for use in potentially explosive atmospheres. Refrigeration systems containing ammonia may fall under the scope of this directive, especially in industrial settings where explosive atmospheres are present.
- ATEX Directive 99/92/EC sets the minimum requirements for ensuring the health and safety of workers operating in potentially explosive atmospheres.
- EN IEC 60079 Standard series deals with the requirements for electrical equipment in explosive atmospheres. Of particular interest to ammonia:
    - EN IEC 60079-0:2018 which sets the specifications and requirements for the construction and testing of equipment to be used in explosive atmospheres.

- o EN IEC 60079-10-1:2015 which defines the classification of the zones where leakage of flammable material or hazardous substance might occur.
- o EN IEC 60079-14:2014 which deals with the design and manufacturing of electrical components located in explosive atmospheres.
- o EN IEC 60079-15:2019 which sets the requirements for the protection of electrical equipment through suitable enclosures (type 'n' protection).

In most countries national legislation does not impose additional restrictions to those set by the EU directives and relevant Standards. However, certain countries have set stricter requirements on the use of ammonia, beyond those of the EU Directives and Standards, which hinder its wider uptake in refrigeration and air conditioning systems. Relevant legislation in the countries that host demo sites was presented in Deliverable 'D2.3 - Analysis of relevant legislation and standards for system operation'. From the remaining countries that have been selected for the replication analysis, Italy and France have set stricter requirements than the relevant EU directives and Standards described above on the use of Ammonia as a refrigerant whilst the rest comply with the limitations of the EU directives.

In Italy the following Ministerial Decrees restrict the use of low GWP refrigerants according to the building use and mandate that only non-toxic and non-flammable refrigerants may be used (D.M., 1992, D.M., 1994, D.M., 1996, D.M., 2002, D.M., 2006, D.M., 2010, D.M., 2014, D.M., 2014, D.M., 2014, D.M., 2019, D.M., 2020). The restrictions set according to the above Ministerial Decrees allow ammonia to be used only in industrial installations without public occupancy (Birchby et al., 2022).

In France, Ministerial Decree 25/06/1980 sets restrictions on the use of flammable refrigerants for specific public access buildings (Ricardo Energy & Environment, 2015). Codes CH35 and GH37 restrict the use of flammable refrigerants in public and high-rise buildings respectively (Birchby et al., 2022). French codes provide exemptions on the use of ammonia; however, the maximum permissible charge is limited to 150 kg (Ricardo Energy & Environment, 2015).

As described in (Cano, 2023) the optimum setup of the Ministor system according to the restrictions of the EN 378 Standard was a double indirect system. Since the system is proposed for use in residential buildings (Access Category A) it was determined that the optimum manner to install the system was to keep the ammonia-containing parts in an outside ventilated shelter, i.e. the system is characterized as location is 'Class III - Machinery room or open air' which according to EN 378 is not subject to any restrictions regarding the charging load. This configuration allows the system to have the required permissible charge for meeting the building's requirements in some cases even under the stricter restrictions set by the national legislation. Therefore, this configuration will be considered when considering its use in different building typologies.

2.2 Installation procedures and challenges

At first, a short summary for the preparation works in the Thessaloniki pre-pilot is provided, with more detail available in the relevant deliverable D6.3.

In terms of regulatory compliance, the installation and operation of ammonia-containing systems must follow EU Standard EN-378. As such safety measures are of paramount importance; thus, detectors were installed to automatically stop gas flow in case of a leak, and at least one protective suit for handling ammonia was available on site. Furthermore, all fire safety measures outlined in relevant legislature acts were adhered. More information on the safety measures may be found in D4.5.

The installation site in Thessaloniki was selected as to minimize visual disturbance and ensure proximity to the Smart Home to reduce costs and heat losses through the necessary piping. A 2-meter distance between the ammonia machinery rooms (hereby called MiniStor system) and nearby buildings' emergency exits was maintained as per EN-378 standard. The discharge of undiluted

ammonia into the sewage system was strictly avoided, and liquid waste ammonia concentration was maintained below the maximum allowable limit of 60 mg/L.

For optimal space utilization and performance, the solar field was installed near the MiniStor system. The installation followed country-specific guidelines to optimize the azimuth angle and slope for maximum annual solar energy harvesting. At the pre-pilot site, the solar field was installed with an azimuth angle of 0° and a slope of 40°. Additionally, the electrical subsystem was designed in such a way as to ensure a continuous power supply, either from the photovoltaic thermal (PVT) panels or the external electrical grid. Insulated underground pipes and cables connected the solar field to both the MiniStor system and the building infrastructure.

2.2.1 Logistical challenges and transportation considerations

Several logistical challenges were encountered during the shipment and installation of the MiniStor system and its components at the Thessaloniki pre-demo site. The key components of the MiniStor system were supplied by PSYCTOTHERM and ENDEF. Due to its weight—approximately 1,800 kg—and the fact that the system was transported with all the mechanical equipment preinstalled, the MiniStor container required meticulous transportation planning.

One major challenge was the difficulty in manoeuvring the delivery truck close to the designated installation site due to a height difference between the closest road and the final location of the system. As a result, the container had to be unloaded from the truck at a roadside location and then lifted into place using a crane (as illustrated in Figure 1). Once positioned, the system had to remain stationary for 24 hours to allow the refrigerant to stabilize before testing, commissioning, and integration with the existing infrastructure could proceed. Figure 2 displays the MiniStor installation at the pre-demo site in Thessaloniki.

To facilitate future installations, it is recommended to:

- Inform vehicle owners in advance to prevent parking obstructions near the delivery site on the installation date.

- Use crane assistance if direct truck access is not feasible.

- Implement additional caution when shipping MiniStor via sea transport. The system must be enclosed within a standard shipping container due to ammonia transport regulations.

2.2.2 Installation process at the Thessaloniki pre-demo site and standard installation procedures

The MiniStor system was installed near the Smart Home within CERTH premises. The installation was performed by an external contractor in collaboration with CERTH's own technical services. The process required a tendering procedure to hire a contractor for the necessary hydraulic and electrical connections between MiniStor and the building, as well as the cement slab on which the system is placed. The contractor was also responsible for assembling the solar field and ensuring the proper connection of the hydraulic and electrical components. Since regulations require different departments (e.g., legal, technical) to review and approve the process, the tendering procedure can be time-consuming, therefore it is strongly recommended that the process begin 3 to 5 months prior to the planned installation date. Additional details on the installation process can be found in Deliverable D6.3.

Figure 1: Unloading MiniStor on the cement slab with a crane in the Thessaloniki pre-demo site

Figure 2: MiniStor installed in the Thessaloniki pre-demo site

The typical installation process includes the following key steps:

- Installing the solar PVT panels and/or FPC collectors: The panels are installed according to the hydraulic and electrical design provided by ENDEF.

- Connecting hydraulic and electrical systems: Insulated pipes are installed to transfer the heat removal fluid from the solar field to the MiniStor system and the building's heating/cooling system. Sensors and thermostats are integrated to monitor temperature levels and adjust flow accordingly.

- Pre-assembled hydraulic components: The MiniStor system is designed with pre-assembled critical components, including the TCM reactor, inertia tank, solar station, solar controller, and most sensors and actuators. This pre-assembly reduces installation complexity by requiring only three external hydraulic connections between MiniStor and the solar field.

- Control system integration: It is recommended to incorporate the solar field control system into the main MiniStor PLC rather than using a separate controller for the solar field. Additionally, in institutions with strict IT security protocols (e.g., CERTH), the connectivity of the MiniStor PLC system to the internet must be verified in advance.

The Electrical Energy Storage System (ESS) should be positioned considering the local climatic conditions:

- Severe weather conditions: The ESS should be installed indoors with air conditioning to ensure proper operation.
- Mild weather conditions: It can be installed outdoors adjacent to the MiniStor system to optimize space utilization. In this case, protective coverings should be used to shield the system from direct sunlight and rain.

The regulatory framework for ESS integration varies by country and must be carefully examined. A detailed analysis of regulatory limitations is provided in Deliverable D3.9. For example, at the Thessaloniki demonstration site, direct interaction between the ESS and the grid is prohibited for charging lithium-ion batteries or exporting energy. Instead, a price signal is used to determine whether electricity should be sourced from batteries, PVT systems, or the grid.

If MiniStor is to be connected to a heat pump, the following considerations apply:

- A heat pump capable of producing 55°C to 65°C water temperature is recommended. Ideally, it should also support 80°C for rapid TCM charging.
- A bi-block air-to-water heat pump (with separate indoor and outdoor units) offers greater installation flexibility.
- A parallel integration approach is preferred to optimize energy transfer between the PVT solar field, heat pump, and the inertia tank.

Further details on heat pump installation and operation are available in Deliverable D3.7, which covers hydraulic, electrical, and refrigerant circuit configurations, safety measures, and control strategies for optimal performance.

2.2.3 System Testing and Commissioning

The following standard testing procedures were conducted to ensure proper installation and functionality:

- Component inspection: Verifying secure installation and proper connectivity of all system elements.

- Electrical testing: Ensuring correct voltage and current levels in all electrical connections.

- Internet connectivity check: Establishing remote communication with the technology provider for maintenance/safety purposes.

- Leak and pressure testing: Filling the solar circuit with a 25% volume glycol-water mixture, pressurizing it to remove excess air, and checking for leaks.

Following the commissioning of the MiniStor system in Thessaloniki, the following points were made and communicated to the other partners:

1. The solar controller has a small internal battery. If it is left without external power for more than 2-3 days, it will lose its programmed inputs and will reset to factory defaults. It is advised to save the solar controller configuration in a SD card to retrieve it, in case of long power outages.
2. It is recommended to double-check the calculations for the expansion vessel's dimensioning. The pre-demo site's expansion vessel volume in relation to the total system (solar circuit and TCM circuit) was inadequate. As a result, the expansion vessel capacity must be calculated based on the final circuit architecture, after all the pipes have been installed and measured. Another suggestion is to connect an additional expansion vessel to the TCM tank and internal circuit, excluding the one for the solar hydraulic circuit.
3. The Emetti electrical resistance has a safety fuse, which if the temperature inside the tank increases more than 80°C will pop out. This means that after the temperature drops, the resistance will not turn on if the fuse is not put back into its original position. This is something that might happen if for some reason the external air cooler does not start.
4. The operational pressure of 2-2.2 bars should be reached when the system is fully operational and the temperature in the solar circuit and the buffer are above 35°C. If the system is filled at lower temperatures to a pressure of 2-2.2 bars, during operation the pressure will increase significantly (to more than 3-3.2 bars). If there is any height difference between the Ministor and the solar field, it should be taken into consideration as well.
5. The PVTs must be operated always with the solar controller "ON" to avoid overheating issues in the solar field. Temperatures above 80°C can damage the PVT laminates.
6. In case the system is out of operation, and the electricity is turned off, the PVTs must be covered to avoid overheating and damage to the PV laminate.
7. An emergency command is implemented in the PLC to dissipate heat through the external cooler, in case the inertia tank reaches temperatures above 80°C.
8. During NH_3 charging mode, the heat pump operates to make sure that the NH_3 condenser is properly cooled. If HTF-TY-7 exceeds 40°C it means that the heat pump is not running properly, and the NH_3 compressor must stop, and heat pump operation should be checked.
9. PVT collectors lack a specific spot for the installation of the temperature sensor. It is suggested to improve the manufacturing process by specifying the installation position for this sensor.
10. Due to the lack of visual sensors in the original layout, it is necessary to install supplementary visual sensors in the solar field to facilitate maintenance operations.
11. Challenges encountered during the filling process of the hydraulic circuit. The installation of an auto-filling system was proposed to simplify the filling procedure.
12. The solar field must be installed only a few days before the arrival date of the prototype at each demonstration site. This aims to mitigate overheating of the PVT panels, on the other hand, the PVT support structure and electrical components may be installed prior of the prototype's arrival.

3. Replication potential

Chapter 3 outlines a comprehensive methodology for assessing the replication technical potential of the MiniStor system. This methodology includes the selection of EU regions with harsh climatic conditions and the evaluation of suitable building typologies. The system's performance under different environmental conditions is assessed using simulation results based on the methodology described by Zisopoulos (2023). Due to the constraints of the projects' timeline and the scope of T3.6, the dedicated software tool that will be developed could not be used for this analysis.

3.1   Selection of EU regions with harsh climatic conditions

One of the aims of the feasibility analysis is to evaluate the annual performance of the MiniStor system in a range of potential sites. Thus, the MiniStor model from D3.1 is going to be utilized for obtaining indicative simulation results for several potential buildings in a range of European countries as well as outside the EU; countries from the Mission Innovation initiative were considered for identifying suitable sites outside the EU.

Mission Innovation is a global initiative between 23 countries (Australia, China, Chile, Morocco, Norway, USA to name a few) and the EU (represented by the European Commission) with a goal to promote and accelerate innovation in clean energy towards achieving the Paris Agreement targets (Mission Innovation, 2024).

The first step in the analysis involves identifying sites with climatic conditions distinct from the existing pre-demo and demo sites in the MiniStor project. Extreme temperatures, along with significant precipitation and wind events, are known to impact HVAC system performance (Stiles Services, 2024). Therefore, locations with particularly harsh climate conditions were also included in the study.

In the context of the MiniStor project, harsh climatic conditions are defined as those characterized by cold winters with moderate solar radiation potential, enabling the effective operation of photovoltaic thermal (PVT) collectors and flat plate collectors (FPCs) used in MiniStor. To classify the selected sites, the Köppen-Geiger climate classification (Ochoa, 2023) was utilized. Figure 3 presents the Köppen-Geiger climate zones for Europe (Beck, 2018).

In Europe, there are 18 possible climate types according to parameters such as mean annual temperature, annual precipitation and its distribution during the year. They are coded according to letters, with the positions of these letters representing features of the climate types.

The five main climate groups are described through the first letter as:

(A) tropical zone,

(B) arid zone,

(C) temperate zone,

(D) cold zone, and

(E) polar zone.

A second letter is used to describe the level of precipitation, and a third letter defines a dominating attribute of air temperature.

For example, Cfc defines the temperate climate with cold summer, while Cfb defines a temperate climate with warm summers.

In Figure 3 (Beck, 2018), all the climatic zones zones in Europe are provided in the legend.

14
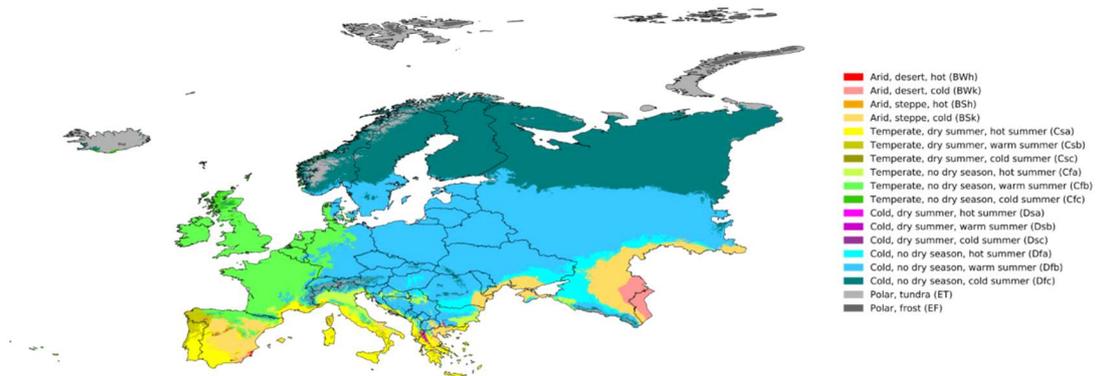
Figure 3: Climate zones based on Köppen-Geiger climate classification for Europe

The climatic zones of the MiniStor demo sites (as discussed in Deliverable D2.2) are presented in Table 1. Even though some local climate variations from the main classifications might exist, it can be seen in Figure 3 that the climate types of these demos' sites are representative of most European cities.

The southernmost part of Spain and Portugal as well as large regions in Italy and Greece have Csb climate similar to the Kimmeria demo site, continental areas in Spain and Greece have Bsk climate like Thessaloniki, much of western Europe has a Cfb climate similar to Santiago del Compostela and Cork whilst most of central and eastern Europe is characterised as Dfb (Sopron).

Table 1: Climate classifications of the Ministor demo sites

Location	Climate classification
Santiago del Compostela	Cfc
Sopron	Dfb
Thessaloniki	Csb
Kimmeria	Csb
Cork	Cfb

To assess the replicability of the MiniStor system under varying climatic conditions, additional locations were selected. These sites were chosen based on:

1. Geographical diversity across Europe.

2. Distinct climatic conditions to evaluate system performance under different temperature and precipitation patterns.

3. Significant market potential, considering residential building distribution.

According to the EU Building Stock Observatory (2024), residential buildings in Germany account for 19% of the total residential building stock in EU-27 countries (3,473 million m²). France and Italy contribute 16% and 15%, respectively. Additionally, Cyprus, which experiences hot semi-arid conditions, was included to assess the system's ability to cover cooling demand in the warmest European climates. The selected seven countries account for a combined 11,145 million m² of residential floor area—over 60% of the EU's total residential building stock (18,408 million m²). Beyond the EU, Norway was included as a Mission Innovation country to examine the MiniStor system's performance under extreme cold conditions.

The list of cities selected for the assessment of the MiniStor system along with some main characteristics of the climatic conditions relevant to the system's performance are presented in Table 2 below.

The weather data for the calculation of these parameters were obtained by the Meteonorm database (Meteonorm, 2020)

Table 2: Selected sites for investigating the applicability of the Ministor system under different climatic conditions and characteristics of their climate

City	Country	Climate classification	Average Daily Temperature		HDDs (15ºC)	CDDs (24ºC)
			Tmax (ºC)	Tmin (ºC)		
Larnaca	Cyprus	Hot semi-arid	31.2	6.9	668	441
Athens	Greece	Temperate, dry summer, hot summer	31.6	5.5	1,115	448
Rome	Italy	Temperate, dry summer, hot summer	29.5	3.2	1,570	163
Porto	Portugal	Temperate, dry summer, warm summer	24.2	5.5	1,415	23
Paris	France	Temperate, no dry season, warm summer	22.3	-0.2	3,027	0
Krakow	Poland	Cold, no dry season, warm summer	21.7	-6.7	3,799	0
Berlin	Germany	Temperate, no dry season, warm summer	24.6	-3.7	3,271	8
Hamburg	Germany	Temperate, no dry season, warm summer	22.7	-2.2	3,407	0
Bergen	Norway	Temperate, no dry season, warm summer	17.5	-0.9	3,739	0

The Heating Degree Day (HDD) and Cooling Degree Day (CDD) indexes are useful metrics for associating the climate characteristics in each area to the heating and cooling demand of buildings. Their calculation takes into consideration the difference between the mean daily external temperature and a base temperature (defined as the temperature where no heating/cooling of the building is required). It should be noted that different base temperatures may be applicable to different countries, however for reasons of consistency and to demonstrate the differences of the climatic conditions between the various sites the commonly used base temperatures of 15°C for heating and 24°C for cooling were selected (Kajewska-Szkudlarek, 2023). The HDDs and CDDs for a certain period of time are calculated according to the following equations (Eurostat, 2020):

$$HDD = \sum_i(18°C - T^i_m), \text{ when } T_m \leq 15°C$$

Equation 1

$$HDD = 0 \text{ , when } T_m > 15°C$$

$$CDD = \sum_i(T^i_m - 21°C), \text{ when } T_m \geq 24°C$$

Equation 2

$$CDD = 0 \text{ , when } T_m < 24°C$$

Where,

T^i_m = the mean daily temperature of day i. This is determined as the arithmetic mean value of the daily maximum (T_{max}) and the daily minimum temperature (T_{min}) (ASHRAE, 2009) $T_m = \dfrac{T_{max} + T_{min}}{2}$

Equation 3

3.2 Building topology for replicating MiniStor

To assess the replication potential of the Ministor system, its applicability was investigated in different sites and climates considering suitable building typologies in each of the cities and countries identified in the previous section.

To this end, the TABULA web tool serves as a valuable resource for defining suitable building typologies in various countries (TABULA, 2022). The TABULA Web Tool has been developed in the framework of Energy Europe projects "TABULA" (IEE Project TABULA, 2009) and "EPISCOPE" (IEE Project EPISCOPE, 2013) and its main goal is to disseminate typical national residential building typologies to building experts in Europe and track the energy performance of buildings.

It is a user-friendly platform where the user has access to the most typical building typologies met in various countries along with information on construction methods, thermal transmittance values for the main building elements, commonly used building systems and resulting data on energy consumption.

The locations for evaluating the performance of the MiniStor system under different climatic conditions were identified in Section 3.1. A suitable building typology for each country was then selected from the TABULA database. The single-family house (SFH)—either detached or semi-detached—was chosen as the representative building typology for the replication analysis. This selection was based on its similarity to the pre-pilot building, the Smart Home of CERTH/ITI. Additionally, single-family houses were considered preferable due to their lower ammonia charge requirements and the availability of outdoor space for installing the double indirect system with an external machinery room. This choice also helps to circumvent regulatory barriers imposed by national legislation and standards, as outlined in the previous section.

Key parameters such as building size, construction materials, architectural styles, and energy efficiency characteristics were considered to identify the most suitable single-family residential

buildings in each city and country. From the various single-dwelling buildings included in the TABULA database, the most recent construction typologies were selected to align with the construction period and energy efficiency features of the Smart Home.

Each TABULA typology selected has detailed energy balance calculations where the thermal transmittances, also known as U-values, of transmission and ventilation may be extracted. The extracted total (whole building) U-values that contain the transmission and ventilation losses as well as the category based on TABULA web tool and the period of construction are presented for each city in Table 3.

It should be noted that there is no building typology for Portugal from TABULA and therefore data from different sources were selected to find the reference floor area and the U-values (EPBD Portugal, 2018).

For these buildings the heating and cooling loads for a certain period can be determined considering the following equations:

$$Q_{H,i} = U_m \cdot A_{ref} \cdot (T_i - T_b) \qquad \text{Equation 4}$$

where A_{ref} is the reference floor area, i= [1,t_{end}] is the time step, U_m is the average whole building U-value considering transmission and ventilation losses. Similarly, the time dependent cooling load is given by

$$Q_{C,i} = U_m \cdot A_{ref} \cdot (T_b - T_i) \qquad \text{Equation 5}$$

In a similar manner, a simplified evaluation of the heating and cooling needs may be conducted with the use of the following equations, when considering the HDDs and CDDs determined in Section 3.1 (Table 2) for the different locations:

$$Q_H = U_m \cdot A_{ref} \cdot HDD \cdot 24 \qquad \text{Equation 6}$$

$$Q_C = U_m \cdot A_{ref} \cdot CDD \cdot 24 \qquad \text{Equation 7}$$

Where Q_H and Q_C are the annual heating and cooling loads respectively. This simplified annual heating and cooling demand for each building in the various sites is also presented in Table 3.

In order to determine the technical replication potential of the examined cases presented above, the percentage of single-family dwellings in each country was determined. Based on the study European Building Stock Analysis by Eurac Research (Gevorgian et al., 2021) single family dwellings and terrace houses account from 29% to 91% of the building stock in the countries examined; 29% in Italy, 48% in France, 68% in Greece, 71% in Germany, 76% in Poland, 86% in Portugal and 91% in Cyprus.

Furthermore, as the most recent constructions were considered from the TABULA database, only those dwellings constructed after 2010 were taken into consideration when estimating the replication potential of the system. Post 2010 constructions range from 4% to 12%: 4% in Germany, 5% in Greece 7% in Portugal, 10% in Cyprus and 12% in Italy, France and Poland. Overall, it is estimated that these typologies examined roughly account for approximately 504 million m^2 of floor area where the MiniStor system may be installed.

Table 3: TABULA category and period of construction for each selected site location along with basic energy consumption data

City	Country	Building Type (TABULA)		Average whole building U-value (W/m²K)	Reference Area (m²)	Construction period	Q_H (kWh/y)	Q_c (kWh/y)
Larnaca	Cyprus		SFH04	3.6	170	(2014 -)	9,812	6,477
Athens	Greece		SFH04	2	255	(2011 -)	13,648	5,484
Rome	Italy		SFH08	1.7	174	(2006 -)	11,146	1,157
Porto	Portugal	-	-	2	117	(2016 -)	7,946	129
Paris	France		SFH10	1.4	103	(2013 -)	10,476	0
Krakow	Poland		SFH07	1.5	187	(2009 -)	25,575	0
Berlin	Germany		SFH12	1.3	187	(2016 -)	19,084	47
Hamburg	Germany		SFH12	1.3	187	(2016 -)	19,878	0
Bergen	Norway		SFH07	1	184	(2011 -)	16,511	0

3.3 Methodology for replication

In the current section, the methodology used to access the technical potential from the replication of MiniStor is described. The methodology consists of five steps:

1. At first, the sites are selected after investigating EU regions under different climatic conditions and characteristics of their climate. The chosen sites for investigating the applicability of the MiniStor system are presented in Table 3.
2. Next, the building typologies are found as presented in Section 3.3. By choosing the buildings, the heating and cooling loads are easily calculated according to Eqs. 4-5.
3. A time period covering a full cycle of charging/discharging is calculated. A full cycle is usually completed in two to three days and therefore a typical winter and summer time period is defined in order to capture the behaviour of the MiniStor system since the MiniStor model can simulate the MiniStor system for only a set of representative days of the year due to computational cost.
4. The rest of the input data covering the solar field and the operation of the MiniStor system are defined, e.g., solar collector layout, mass flow of solar field to tank, mass flow from buffer tank to TCM reactor and operating pressures.
5. Finally, the MiniStor model is executed and the results for all the regions are obtained.

It is noted that the procedure along with the MiniStor model has been incorporated into a MATLAB tool in order to easily replicate the MiniStor system for any region having meteorological data and building typology.

Part of the MATLAB code developed for the MiniStor replication is presented in Figure 4.

Figure 4: Part of the main MATLAB code for MiniStor replication

Since the first two steps are already presented in Sections 3.1 and 3.3 respectively, here the procedure for defining the typical time period is given. As described in D3.1, time segments of a full cycle (charge and discharge) are considered for the winter and summer period.

The procedure for finding the representative days depends on the outdoor temperature and the corresponding Heating and Cooling Degree Days (HDD, CDD) which affect the heating and cooling demand of the building and the available solar radiation of the site.

To find a representative period with weather conditions very close to the average winter or summer period, a procedure has been derived with the following steps:

1. For each day of the typical meteorological year (TMY), the daily HDD and CDD values as well as the daily total solar radiative energy on a tilted surface are computed. The TMY files

used are derived from the Meteonorm database, which is considered as highly accurate, since it utilizes data derived from meteorological stations.

2. LSA (land surface albedo) is indicative of the difference of the daily HDD, CDD and solar energy on tilted surface values from the average ones defined in step 2. For each day the variable LSA, as defined in Eq. (4.4) of D3.1 is calculated.
3. The daily LSA values are summed over periods of three subsequent days which correspond to a full cycle of charging/discharging of the MiniStor system.
4. The three-day period with the lowest LSA score is chosen to represent weather conditions similar to the average.

A typical full cycle of charging/discharging, that has the lowest LSA values, is found for all the cities leading to the average heating and cooling period. The maximum number of days for a typical full cycle is usually three days. The heating and cooling time duration as well as the heating and cooling demand (total and per m^2) for each building in the various cities is also presented in Table 4. Cities like Berlin, Hamburg and Krakow have increased heating demand. There is an exception here however with the city of Bergen which has a smaller heating demand than the other northern cities due to the smaller average whole building U-value. Cities such as Athens and Rome had lower and more consistent heating demand during the observed average winter season. It is worth noting that Larnaca has a high heating demand due to the high U-value of the building style.

In addition, Larnaca has the highest cooling needs due to its high U-value and high ambient temperatures. Athens likewise has a high cooling requirement, while Rome's is typical. Berge, Berlin, Paris, Krakow, and Hamburg have low cooling demand because there are only a few days with high ambient temperatures, resulting in a low number of cooling degree hours and, as a result, cooling degree days. As a result, cooling demands are excluded for all the aforementioned cities.

The third step of the replication methodology is completed by considering also the solar radiation on the solar field as well as the ambient temperature values. All values are interpolated from the hourly values of the TMY file to 15 min time intervals to coincide with the needed time step of the MiniStor model which is 15 min.

The fourth step includes other input data for the MiniStor model (solar field, buffer tank, thermal system configuration) used for the pre-demo site in Thessaloniki as reported in D3.1. The default solar field includes three rows with one row of five solar hybrid panels (PVTs), a second row of five solar hybrid panels (PVTs) and a third row five solar flat plate collectors (FPCs). The total installed thermal capacity is 16kW$_{th}$ and the peak electricity generation is 2.65 kW$_e$. All the corresponding data are given in Tables 5 and 6 from D3.1.

Finally, the MiniStor model is executed for all the cities and their corresponding heating and cooling periods, and the results are presented in the next Section.

Table 4: Typical heating and cooling period for each city

Location (Lat., Long.)	Heating period duration	Cooling period duration	Q$_H$ (kWh)	Q$_C$ (kWh)	Q$_H$ (kWh/m^2)	Q$_C$ (kWh/m^2)
Athens (37.98, 3.73)	November – April	May - September	77	33	0.44	0.19
Bergen (60.40, 5.32)	September - June	July- August	121.8	-	0.70	-
Berlin (52.52, 3.41)	September - May	June - August	167.9	-	0.96	-
Hamburg (53.55, 10.0)	September - June	July- August	163.7	-	0.94	-
Krakow (50.05, 9.95)	September - May	June - August	166.7	-	0.96	-
Larnaca (34.93, 3.63)	December- March	May - October	81	47.3	0.47	0.27
Paris (48.87, 2.35)	September- May	June - August	129.7	-	0.75	-
Porto (41.15, -8.63)	October- May	June - September	69.8	-	0.40	-
Rome (41.90, 12.50)	September - April	June - September	115.8	12.5	0.67	0.07

Table 5: Main specifications of the considered flat plate collectors

	Considered FPC model	
Model	FMAX 2.4	FMAX 2.0
Dimensions L x W x T (m)	1.230 x 1.930 x 0.086	1.010 x 1.980 x 0.086
Gross area (m^2)	2.37	2
Absorber area (m^2)	2.23	1.87
Thermal specifications		
Fluid content (lt)	1.7	1.4
Fluid flow rate (kg / m^{2}h) *	20 - 40	
Optical efficiency, η_0 (-) **	0.823	
Heat loss coefficient, α_1 (W/m^{2}K) **	3.36	
Heat loss coefficient, α_2 (W/m^{2}K^2) **	0.013	
* values applying to absorber area, ** values applying to gross area		

Table 6: Thermal system design parameters

Demo site	Sopron	Kimmeria	Cork	Thessaloniki	Santiago
PVT – Solar Collector Layout	9 PVT (Glazed) 6 FPCs (ESCOSOL FMAX 2.4)	- -	4 PVT (Glazed) 4 FPCs (ESCOSOL FMAX 2.0)	10 PVT (Glazed) 5 FPC (ESCOSOL FMAX 2.4)	20 PVT (Unglazed)
Mass flow from solar field to tank (kg/h)	554	-	400	500	1000
TCM size (kWh)	17.5				
PCM size (kWh)	Hot PCM – 3.5 kWh (SU58 material) Cold PCM – 6 kWh (SU11 material)				
Tank size (lt)	60				
Operating pressure of TCM	2 (Winter –Spring/Autumn cases) 3 (Summer cases)				

decomposition reaction (bar)					
Average and Extreme winter case scenarios					
Initial Temperature of buffer tank and cell (°C)	Thigh: 40 Tlow: 35 Tcell:10	-	Thigh: 40 Tlow: 35 Tcell:10	Thigh: 40 Tlow: 35 Tcell:10	Thigh: 40 Tlow: 35 Tcell:10
Mass flow from buffer tank to TCM reactor (kg/h)	360	468	360	360	1000
Operating pressure of TCM synthesis reaction (bar)	6	6	6	6	6.5
Activation temperature of decomposition reaction (°C)	Average 44 Extreme 50	Average 60 Extreme60	Average: 44 Extreme: 44	Average: 50 Extreme: 44	Average: 65 Extreme: 65
Average and Extreme summer case scenarios – for Cork and Santiago the average spring-autumn scenario is depicted					
Initial Temperature of buffer tank and cell (°C)	Thigh: 60 Tlow: 55 Tcell:20	-	Thigh:40 Tlow: 35 Tcell:10	Thigh: 60 Tlow: 55 Tcell:20	Thigh: 40 Tlow: 35 Tcell: 10
Mass flow from buffer tank to TCM reactor (kg/h)	360	468	360	500	1000
Operating pressure of TCM synthesis reaction (bar)	5	5	6	5	6.5
Activation temperature of decomposition reaction (°C)	Extreme: 70	Average: 70 Extreme: 70	Average: 44	Average: 70 Extreme: 70	Average: 65 Extreme: 65

24

4. Feasibility analysis

The feasibility analysis evaluates the MiniStor system's performance across selected buildings, cities, and demonstration sites. The buildings at the demo sites differ from those in the TABULA database (TABULA, 2022) in terms of U-values, floor area, and usage patterns.

The primary difference in this analysis, compared to the MiniStor model described in D3.1, is the method used to estimate photovoltaic (PV) energy generation. Instead of using the MiniStor model for PV generation estimation, annual solar electricity calculations from the Photovoltaic Geographical Information System (PVGIS) are used.

The Photovoltaic Geographical Information System (PVGIS) (Huld, 2012) is a powerful tool for analyzing and estimating solar radiation and PV system performance in various geographical regions across Europe.

Developed by the Joint Research Centre (JRC) of the European Commission, PVGIS is one of the most widely used and reliable resources for predicting energy generation from photovoltaic (PV) systems. PVGIS provides a range of data related to solar electricity, including detailed information on solar irradiance, temperature, and meteorological conditions for different regions. Specifically, it includes data on direct, diffuse, and global horizontal irradiance, as well as historical climatic data, which can be crucial for understanding seasonal and yearly variations in solar potential and climate. Additionally, PVGIS provides data on average daily and monthly irradiance, allowing users to observe trends and make informed decisions regarding the sizing, placement, and expected performance of PV systems. Users can further refine their analyses by adjusting input parameters, such as the tilt angle, orientation, and type of the solar panels, to estimate energy output under different scenarios. PVGIS has been widely adopted by researchers, policymakers, and industry professionals for assessing photovoltaic (PV) potential and performance across diverse regions. Researchers have used PVGIS data extensively to model PV system output and understand the effects of climate on solar electricity generation. For instance, researchers used PVGIS to analyse solar radiation across Europe and Africa, providing insights into PV performance under varying environmental conditions and emphasizing the use of solar radiation data calculated from satellite data in the Climate Monitoring Satellite Application Facility (Huld, 2012). Similarly, researchers utilized PVGIS to study how meteorological factors impact energy yield in different climates, underlining its usefulness for optimizing PV installations (Huld, 2015). Furthermore, policymakers refer to PVGIS in strategic renewable energy planning, using its datasets to support the development of solar initiatives that align with national goals (Kakoulaki, 2024).

For this analysis, key assumptions based on PVGIS data and MiniStor configuration parameters include:

- Optimal tilt angles for PV panels in each geographical location for annual production.
- Energy losses of 13%, considering system inefficiencies.
- Data sourced from the PVGIS-SARAH2 database.
- Technical specifications from ENDEF brochures, which provided the MiniStor system with PVT panels.

PVGIS was chosen over the MiniStor model for estimating annual PV energy generation because it provides a more comprehensive full-year dataset, whereas the MiniStor model only simulates 2–3 day charge/discharge cycles. Given the importance of evaluating year-round operation, PVGIS offers improved accuracy in assessing the MiniStor system's feasibility in different locations.

The feasibility study presents results based on a worst-case scenario, in which both the Thermochemical Material (TCM) and Phase Change Material (PCM) storage tanks are initially empty. In real-world applications, however, the storage would typically be pre-charged, allowing for more efficient energy management. To optimize performance, an optimized discharging strategy is proposed and analyzed in Section 4.4.

This Section is divided into four parts. First, results for all cities with and without the use of auxiliary electricity are given for the heating operation of MiniStor. Next, corresponding results for the cooling operation of Ministor are presented. Also, calculations for the annual covered heating, cooling and electricity demand are provided based on the MiniStor model simulations. The first three parts cover results based on the worst-case scenario, beginning with an empty TCM and PCM storage. The fourth and final part presents the optimized scenario, including a comparison of the optimal and worst-case scenarios.

Results include mainly the heat and cooling load coverage by solar energy or other renewable energy sources (RES) and by auxiliary electricity, as well as the state of charge for the phase change material (PCM) batteries in comparison to the heating and cooling loads. The heat load coverage by solar energy is the ratio of heat supplied from MiniStor, charged with solar energy (or other renewable energy sources), to the heating demands. On the other hand, the heat load coverage by auxiliary electricity is the ratio of heat supplied from MiniStor, charged with auxiliary electricity, to the heating demands. This auxiliary electricity comes from the electricity grid; however, if the PVTs generate sufficient electricity, they can partially meet the electricity demands through virtual net-metering. The electricity demands of MiniStor mainly include the needs for the ammonia and the heat pump compressor as well as the backup electricity heater.

All simulations are concluded when a full cycle of charging/discharging (or discharging/charging) is complete (usually in two days), which is a limitation of the analysis.

4.1 Feasibility analysis during the heating period with and without auxiliary electricity

This section presents the results for all the cities mentioned in Section 3, along with the MiniStor demonstration sites. The configuration of the MiniStor system model remains the same as described in D3.1 (where a more detailed explanation of the parameters and numerical results for the demo sites can also be found), and the solar field setup corresponds to that used in the Thessaloniki pre-demo site. Results are provided for Athens, Bergen, Berlin, Hamburg, Krakow, Larnaca, Paris, Porto, and Rome, as well as for the demonstration sites in Cork, Kimmeria, Santiago, Sopron, and Thessaloniki. The heating period considered in this analysis corresponds to the average winter period determined in Section 3.3.

Table 7 presents the results of the MiniStor system's heating operation when the solar field operates without auxiliary grid electricity. The Table includes values for the heating demand (total and per m²), electricity demand over a full charging/discharging cycle, and the solar fraction (fraction of the heating load covered by solar energy). The heat demand covered is expressed as a value between 0 and 1, where 1 indicates that the heating demand is fully met by solar supplied heat. Additionally, the required time to complete one full charging/discharging cycle is reported. If solar radiation is insufficient to complete the charging process, no time value is provided for the corresponding cell.

The results indicate that in Bergen, Berlin, Krakow, Hamburg, and Paris, the MiniStor system fails to achieve full charging due to inadequate solar radiation. Consequently, the heat load coverage by solar energy alone is minimal in these cities and auxiliary grid electricity is required for the system to cover the loads as only a small fraction of heat is utilized when the first decomposition reaction occurs.

Conversely, in Athens, Larnaca, Porto, and Rome, the charging/discharging cycle is completed due to the sufficient level of solar radiation available. The highest heat load coverage by solar energy is observed in Athens, followed by Larnaca and Porto, which exhibit similar heating loads and solar radiation levels. In Rome, however, the average heat coverage is lower due to the longer cycle which results in a higher heating demand. In such cases, a limited use of auxiliary grid electricity could enhance overall system performance by accelerating the full cycle completion and enabling timely recharging of the thermochemical material (TCM) for the next day.

![ministor logo] This project has received funding from the European Union´s Horizon 2020 research and innovation programme under the grant agreement No 869821

Table 7: Heat load coverage for buildings in selected cities for replication without using auxiliary electricity

Location	Time of completion for one full cycle (hr)	Heating demand (kWh)	Heating demand (kWh/m²)	Electricity demand (kWh)	Heat load coverage by solar energy
Athens	46	39	0.22	5.5	0.6
Bergen	-	80	0.44	1.6	0.04
Berlin	-	101	0.46	3.5	0.1
Krakow	-	118	0.58	2	0.05
Hamburg	-	128	0.65	3.5	0.1
Larnaca	46	47.6	0.26	5.6	0.43
Paris	-	84	0.37	1.1	0.05
Porto	48.25	47	0.26	5.7	0.4
Rome	60.75	94	0.52	5.5	0.29

It is interesting to present some time dependent results from one full cycle operation of the MiniStor system when it is charged only with solar supplied heat energy.

Results from Rome and Porto are given in Figure 5 and Figure 6 respectively. In both Figures, the heating load (W), the state of charge of PCM and the heat load coverage are presented over time for the average winter period.

In Figure 5, only part of the heating load in the first night is not covered. On the second night the charging is complete, and the discharging process begins to cover the heating loads. However, in Figure 6 it is obvious that there are two nights where the heating load isn't covered. The PCM cannot cover the large heating loads of both nights. Here, it is important to utilize auxiliary electricity to complete the charging process in time and cover the heating loads of the second night. Also, it should be noted that the simulation provides the worst-case scenario as the simulation starts with the TCM storage completely empty.

Charging of the TCM depends on the availability of the solar radiation and the use of auxiliary electricity, while discharging depends on the user and the heating loads of the building.

Figure 5: Heating load (W), state of charge of PCM and heat load coverage over time (hours) for the average winter period and for the building in Porto

Figure 6: Heating load (W), state of charge of PCM and heat load coverage over time (hours) for the average winter period and for the building in Rome

The MiniStor system can be charged by using solar radiation only in the selected sites for replication with high solar radiation, e.g., Athens, Larnaca. In Table 8, the heat load coverage for buildings in the cities with more harsh climatic conditions is presented. Results for the demo sites are also included since auxiliary electricity was used for the average winter period. Here, we have two forms of the heat load coverage, one where it states how much is covered by solar energy and another by auxiliary electricity. The time of the completion for one full cycle of charging/discharging is also included.

For the selected sites, MiniStor achieves similar heat load coverage by solar energy in Berlin, Krakow, and Paris, ranging from 0.07 to 0.19. Although the cycle duration is comparable in these cities, heating demands vary significantly. The limited availability of solar radiation increases reliance on auxiliary electricity, as reflected in the elevated heat load coverage by auxiliary electricity values.

28

Santiago shows a remarkable 100% coverage of its heating demand by solar energy since it uses an additional heat pump to assist the solar field for the generation of heat. Here, the additional heat input from the heat pump is considered as part of the PVT system and it is calculated in total with the heat from the PVT panels. Kimmeria has a hybrid heat generation system consisting of a biomass boiler and a solar thermal field that generates heat for MiniStor and therefore we don't need any auxiliary electricity. The hybrid generation system uses both solar thermal energy and a biomass boiler, depending on the heating needs. MiniStor in Thessaloniki has significant heat load coverage by solar energy since it has relatively small heating needs in comparison to other demo sites and high solar irradiance. Cork and Sopron present similar behaviour with a heat load coverage by solar energy of around 0.12-0.13. The remaining heating for the charging of MiniStor comes from auxiliary electricity.

The operation of MiniStor significantly changes when solar radiation is insufficient, requiring auxiliary electricity as the primary heat source. Figure 7 illustrates this operation in Berlin, depicting heating load (W), electric heater load (W), PCM state of charge, and heat load coverage over time. Unlike the scenario in Figure 5, solar supplied heat is insufficient to charge the TCM on the first day. Charging only commences with auxiliary electricity on the morning of the second day. The electric heater supplies heat, charging MiniStor and subsequently releasing heat via the heat pump to meet heating demands. However, due to limited heat availability, the PCM storage never fully charges, as most of the heat is directly consumed by the building. It is noted that MiniStor primarily depends on solar radiation for charging, with auxiliary electricity utilized only when necessary.

Table 8: Heat load coverage for buildings in cities for replication with the use of auxiliary electricity

Location	Time for one full cycle (hr)	Heating demand (kWh)	Heating demand (kWh/m^2)	Electric demand (kWh)	Heat load coverage by solar energy	Heat load coverage by auxiliary electricity
Bergen	49	80	0.44	24	0.07	0.22
Berlin	41	83	0.46	21	0.14	0.18
Krakow	42.75	105	0.58	25	0.07	0.24
Hamburg	47.5	117	0.65	22	0.09	0.17
Paris	41.25	66	0.37	22	0.19	0.18
Cork	46.75	128	0.71	14	0.13	0.15
Kimmeria	24.5	51.5	0.68	6.2	0.37	-
Santiago[2]	23.25	22.4	0.28	18.8	1	0
Sopron	30.75	83.5	0.47	22.4	0.12	0.22
Thessaloniki	44.25	36	0.72	14	0.59	0.24

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[2] Supplying heat to Santiago MiniStor is done by PVTs and heat pump.

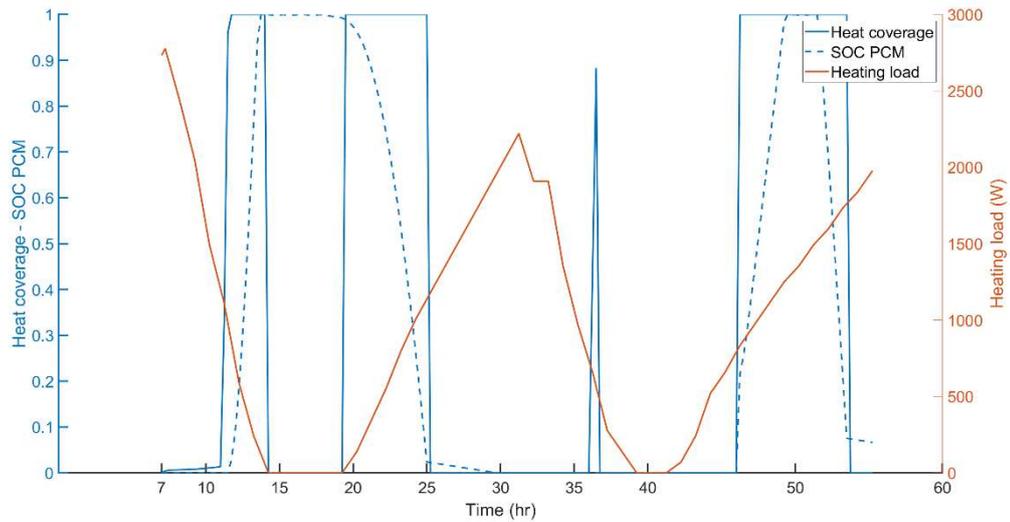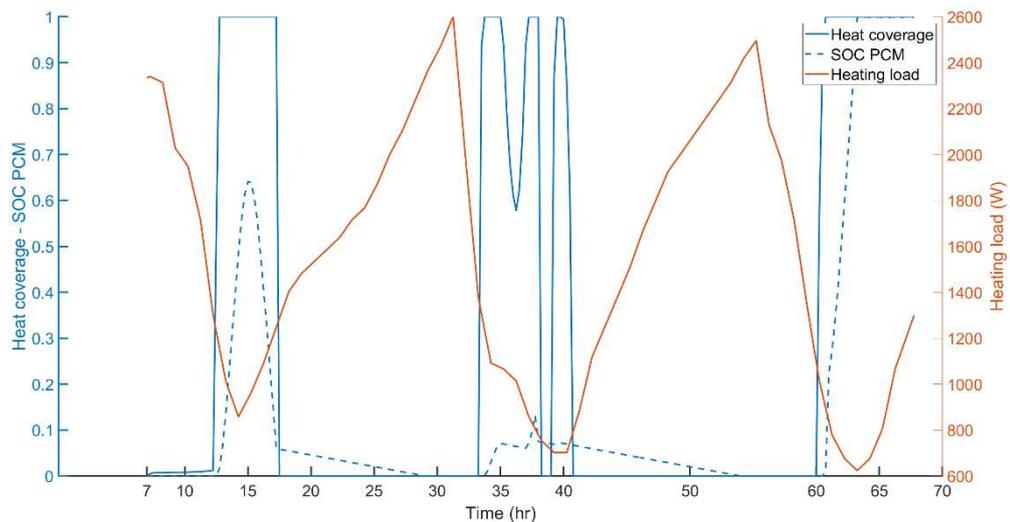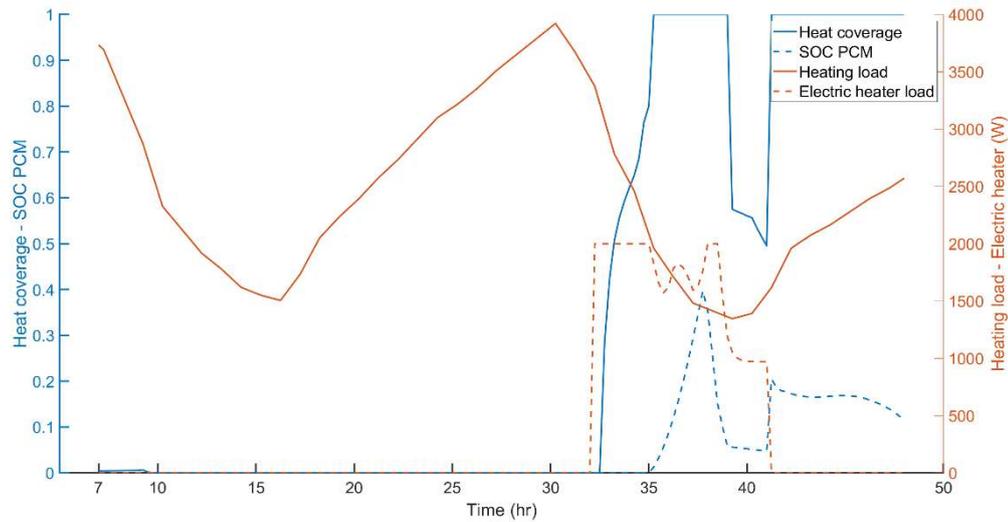**Figure 7: Heating load (W), electric heater load (W), state of charge of PCM and heat load coverage over time (hours) for the average winter period and for the building in Berlin**

4.2   Feasibility analysis during the cooling period

In Table 9, results from the cooling operation of the MiniStor model are presented. The total cooling and electricity demand over one cycle of charging/discharging as well as the cooling load coverage by solar energy are presented. The required time for completing one full cycle of charging/discharging is also provided in Table 9. Since in Table 3 the cooling demands for Berlin and Porto are small, the results from the cooling operation analysis are omitted. It is noted that charging of MiniStor is achieved with heat coming only from the solar field.

On days with no cooling demand, the system is capable of fully covering domestic hot water needs while also supplying electricity to the buildings. The results indicate that higher solar radiation reduces charging time and consequently shortens the full cycle duration, a trend also observed in D3.1. Additionally, average cooling demands vary significantly, with the lowest recorded in Rome (4 kWh) and the highest in Thessaloniki (59 kWh). Cooling load coverage also varies across locations, with Rome exhibiting the highest coverage (0.78) and Thessaloniki the lowest (0.13).

The high cooling load coverage in Rome can be attributed to the combination of strong solar radiation and relatively low cooling demand. In contrast, Thessaloniki's building, an office space, has substantial cooling requirements due to high ventilation loads. Similarly, the building in Kimmeria experiences high cooling demands due to its large surface area. Overall, MiniStor is capable of covering more than 50% of cooling loads in most residential buildings across southern Europe.

To further illustrate the system's performance, Figure 8 presents time-dependent results from a full-cycle cooling operation in Athens. The figure depicts the cooling load (W), the state of charge of the phase change material (PCM), and the cooling load coverage over time during the average summer period. Initially, the thermochemical material (TCM) must be charged before the discharging process can begin, allowing the generation of chilled water through ammonia evaporation. Cooling load coverage increases gradually, reaching a peak around 15–16 hours and maintaining a high level before slightly decreasing toward the end of the cycle. The TCM reaches full charge after approximately 14 hours. The cooling load starts low, rises gradually, and then increases sharply around the 10-hour mark, peaking at noon before declining steadily. As cooling demand rises, cooling load coverage also increases, indicating synchronization between demand and system output. The peak cooling load coincides with the highest cooling production by MiniStor, highlighting its responsiveness to increased demand. As cooling demand decreases in the evening, the state of charge of the cold PCM begins to rise. Since demand is lower but ammonia evaporation

continues to generate chilled water, some cooling energy is stored. This stored energy can then be used to cover a portion of the cooling demand the following day.

Table 9: Cooling load coverage for buildings in selected cities for replication

Location	Time for one full cycle (hr)	Cooling demand (kWh)	Cooling demand (kWh/m^2)	Electricity demand (kWh)	Cooling load coverage covered by solar energy
Athens	21.5	8.3	0.05	2.4	0.53
Larnaca	20.75	16.7	0.43	2.3	0.46
Rome	21.25	4	0.02	2.3	0.78
Thessaloniki	21	59	1.18	2.1	0.13
Kimmeria	22.5	32.5	0.43	2.4	0.31
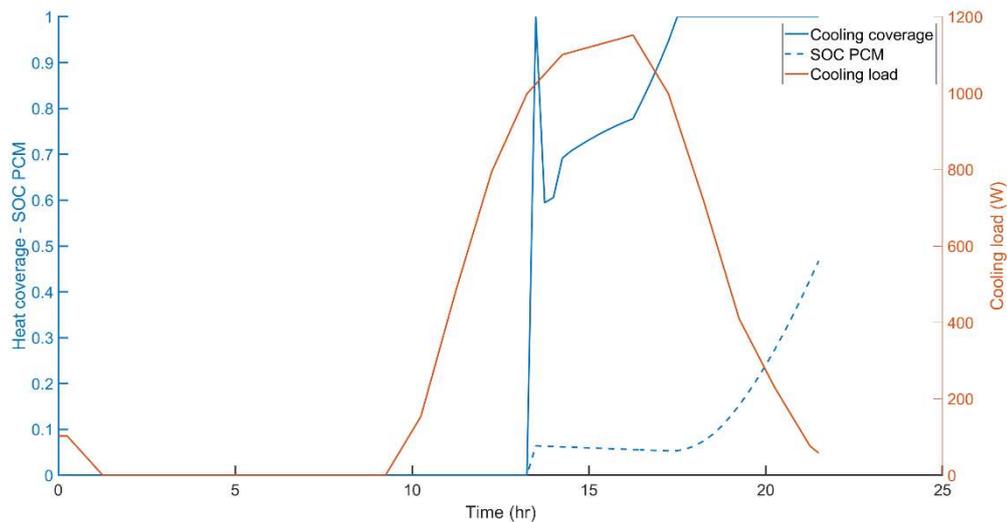
Figure 8: Cooling load (W), state of charge of PCM and cooling load coverage over time (hours) for the average summer period and for the building in Athens

4.3   Annual performance of MiniStor

To assess the extent to which MiniStor can meet annual heating and cooling demands using solar energy, a preliminary analysis is performed. This analysis is made based on the annual heating and cooling data provided in Table 3 and the simulation results from Table 8 and 7. At first, the rate coverage per hour that MiniStor can cover in a full cycle of charging/discharging is calculated and then we apply the coverage rate to the annual heating and cooling demand in order to calculate the annual covered heating and cooling demand respectively. The annual electricity production is provided by PVGIS 5.2.

The results for the annual covered heating demand are reported in Table 10 for the buildings in the cities of Athens, Larnaca, Rome and Porto. The electricity production (kWh) for the heating period of each city is also included. These cities are reported first as the solar field of MiniStor can provide the necessary heat for the charging of the TCM reactor without using auxiliary electricity. The

annual heat demand coverage by solar energy ranges from 0.33 to 0.43 which is a value close to the targets of MiniStor which is to a RES on-site average use of 50%. Keeping in mind that the simulation considers the worst-case scenario (starting with an empty TCM and PCM storage), the goal set by the project seems feasible even with the reduced capacity of the TCM reactor. The electricity production is calculated for the heating period of each site as it denoted in Table 4. The production is similar in Athens, Rome and Porto due to the same size of solar field and the similar solar radiation as well as heating period per site.

Similar to Table 10, results for the annual covered heating demand are presented in Table 11 for the buildings in the cities of Paris, Krakow, Berlin, Hamburg and Bergen as well as the demo sites of Cork, Kimmeria, Santiago, Sopron and Thessaloniki. Here, the difference is that charging of the TCM reactor is done by solar energy and auxiliary electricity. The lowest coverage is seen for areas with the harshest climate conditions, e.g., Bergen, and Krakow. In Paris, solar energy meets 25% of the heating demand, with a total coverage of 50%, showing a balanced approach to integrating solar energy. Berlin and Hamburg show moderate solar contributions with 13% and 10% respectively, and total coverages of 30% and 28%. Next, the highest percentage is achieved for the MiniStor in Sopron, where 66% of the charging heat comes from the solar field and the other auxiliary electricity. In Thessaloniki, solar energy covers 47% of its heating demand with a total coverage of 66%. The TCM reactor in the demo sites of Kimmeria and Santiago is charged with a hybrid heat generation system consisting of a biomass boiler and a solar thermal field and a heat pump respectively. The total heating demand coverage is not provided since auxiliary electricity is not required. In Kimmeria, a 30% coverage by RES is observed, and a 90% coverage in Santiago due to the use of an external heat pump. Also, Santiago has the highest electricity generation (kWh) during the heating season due to its large number of PVTs and high solar potential. Cork has the lowest number of PVTs and small solar potential leading to the lowest electricity production.

In general, an annual simulation of the MiniStor model would be required to have a more accurate value which can be based on D3.10. Nevertheless, from the current methodology it is evident that MiniStor can cover from 25% to 66% of the annual heating needs in cities throughout Europe even though there is need for auxiliary electricity in cities with more harsh climatic conditions. As the TCM storage is limited due to the regulations for ammonia, the remaining load should be covered by an auxiliary heater.

Table 10: Annual heating demand covered by MiniStor without using auxiliary electricity

City	Country	Building (TABULA)	Q_H (kWh/y)	Covered heating demand (kWh/y) by solar energy	Annual heating demand coverage by solar energy	Electricity production (kWh) for the heating period
Larnaca	Cyprus	SFH04	9,812	3,898	0.4	1941
Athens	Greece	SFH04	13,648	4,456	0.33	2215
Rome	Italy	SFH08	11,146	3,931	0.35	2425
Porto	Portugal	-	7,946	3,413	0.43	2485

Since MiniStor is designed to cover mostly heating loads, the coverage of cooling loads is a supplementary operation which will increase the economic feasibility of the system. From Table 3 it is apparent that the cooling loads are zero or very small for most cities and therefore results are presented only for Athens, Larnaca, Rome, Kimmeria and Thessaloniki. The annual covered cooling demand and the coverage by solar energy are reported in Table 12 for the buildings in these cities. It is noted that the cooling operation doesn't need the electric backup heater since the solar field supplies sufficient heat for the charging of MiniStor. It is evident that MiniStor can cover from 33% to 100% of the annual cooling needs in cities throughout southern Europe. The MiniStor in Larnaca

produces the most electricity (kWh) during the cooling period due to the high solar potential and the extended cooling season.

Table 11: Annual heating demand covered by MiniStor with the use of auxiliary electricity or other RES

City	Country	Building (TABULA)	Q_H (kWh/y)	Covered heating demand (kWh/y) by solar energy	Annual heating demand coverage by solar energy	Covered heating demand (kWh/y)	Annual heating demand coverage	Electricity production (kWh) for the heating period
Paris	France	SFH10	10,476	2,663	0.25	5,186	0.5	2062
Krakow	Poland	SFH07	25,575	1,506	0.06	6,670	0.26	1912
Berlin	Germany	SFH12	19,084	2,483	0.13	5,675	0.3	1860
Hamburg	Germany	SFH12	19,878	1,942	0.1	5,610	0.28	2049
Bergen	Norway	SFH07	16,511	1,001	0.06	4,148	0.25	1544
Cork	Ireland	-	17,100	3,118	0.18	6,716	0.39	482
Kimmeria[3]	Greece	-	22,350	6,813	0.30	6,813	-	-
Santiago[4]	Spain	-	9,290	8,440	0.91	8,440	-	2159
Sopron	Hungary	-	4,331	2,854	0.66	8,088	1.87	1356
Thessaloniki	Greece	-	8,973	4,205	0.47	5,915	0.66	1941

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[3] Supplying heat to Kimmeria MiniStor is done by a hybrid heat generation system consisting of a biomass boiler and a solar thermal field.

[4] Supplying heat to Santiago MiniStor is done by PVTs and heat pump.

Table 12: Annual cooling demand covered by MiniStor

City	Country	Building (TABULA)	Q_c (kWh/y)	Covered cooling demand (kWh/y) by solar energy	Annual cooling demand coverage by solar energy	Electricity production (kWh) for the cooling period
Larnaca	Cyprus	SFH04	6,477	3,242	0.5	2739
Athens	Greece	SFH04	5,484	1,792	0.33	2258
Rome	Italy	SFH08	1,157	1,286	1.1	1820
Thessaloniki	Greece	-	8,520	3,199	0.38	1730
Kimmeria	Greece	-	4,350	6,074	1.40	-

Figure 9 illustrates the electricity production during heating and cooling operation of MiniStor across various European cities, showcasing distinct regional differences in energy demands. In the cities of Athens, Bergen, Berlin, Krakow, Larnaca, Hamburg, Paris, Rome, Porto and Thessaloniki the solar field consists of ten PVTs and five solar thermal collectors, while in the demo sites the solar fields differ. In Sopron there are nine PVTs and six solar thermal collectors. In Cork, there are 4 PVTs and four FPCs. Thus, the electricity production varies between the selected cities and the demo cities due to the solar potential and the solar field configuration.
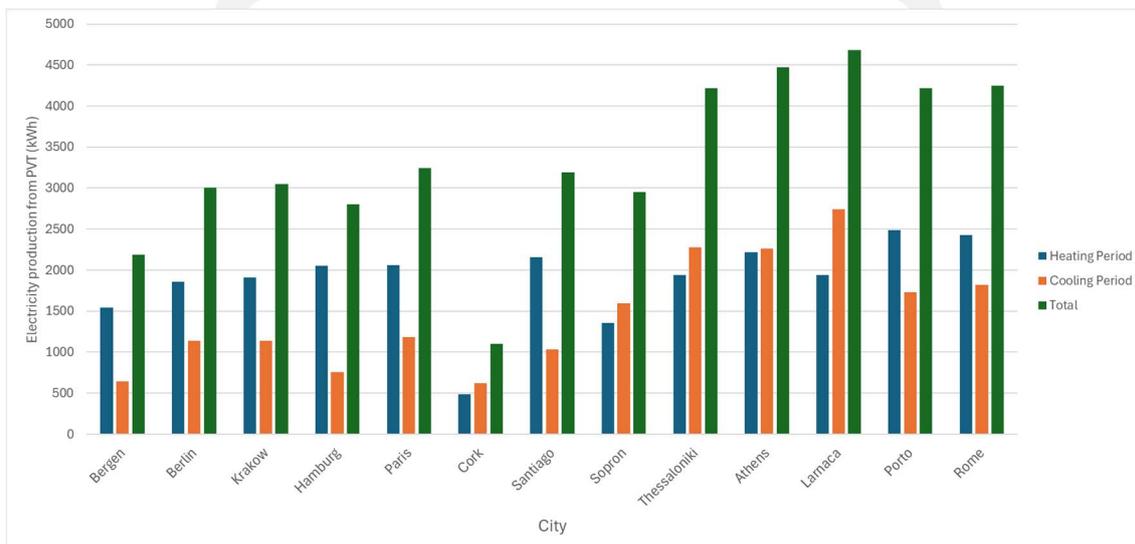

Figure 9: Electricity production (kWh) during the heating and cooling period as well as its total for all demo sites and selected cities

Santiago leads with the highest total electricity production (3912 kWh/y), predominantly during the heating period (2159 kWh/y), while cities like Larnaca and Athens exhibit significant electricity production during cooling operation (2258 kWh/y and 2739 kWh/y, respectively). In Santiago, the solar field consists of 20 PVTs and therefore it is reasonable to have the largest production. In addition to these cities, Thessaloniki and Rome present high electricity production, with substantial production for both heating and cooling operation of MiniStor. Low production cities like Cork and Bergen show relatively balanced yet minimal electricity production for both periods. However, here it is important to note that there is no MiniStor cooling operation in Cork, Bergen, Berlin, Hamburg, Krakow, Porto, Sopron and Santiago and therefore the produced electricity is sent to the electricity

34

grid to provide revenue for the owners. On the other hand, the produced electricity in the heating operation is never enough and electricity from the grid as we have seen in Section 4.1 is needed. Thus, during heating operation, the produced electricity is used to cover MiniStor's own electricity needs, whereas during cooling operation, it is either sufficient to fully meet demand (as in Larnaca, Athens, Rome, and Thessaloniki) or is injected into the grid.

Finally, annual results from the MiniStor operation in different sites are summarized in Table 13 for the worst-case scenario. Krakow has the highest annual heating demand (25,575 kWh/y), followed by Kimmeria and Hamburg. In contrast, Sopron has the lowest heating demand (4,331 kWh/y). Santiago has a notably high demand (5,240 kWh/y) for electricity, which is to be expected given that MiniStor charging is done via a heat pump. Cooling demands are highest in warmer cities like Thessaloniki and Larnaca, while cooler northern cities, such as Berlin and Bergen, report minimal cooling needs. In some cities, combining solar and electric heating increases heating demand coverage (e.g., Thessaloniki reaching 5,915 kWh/y from 4205 kWh/y), while in some others (e.g., Bergen) auxiliary electricity does most of the charging of MiniStor. Auxiliary electricity comes from the electricity grid; however, annual electricity generation covers an important amount of MiniStor's electricity consumption in most cities. In terms of cooling demand coverage, Thessaloniki and Larnaca have considerable cooling demands that are met by RES, ranging from 3,199 to 3242 kWh/year. Cities with high renewable energy coverage ratios (Porto, Santiago) are effectively utilizing RES in MiniStor, reducing dependency on conventional energy sources while cities like Krakow, Bergen, and Cork have lower RES coverage ratios (33%, 32%, and 42%, respectively) due to the harsher climate conditions. In southern cities where annual electricity production exceeds MiniStor's consumption, the surplus energy can be used to power additional electric loads or be fed into the grid, enhancing economic gains.

Table 13: Annual heating and cooling demand coverage by RES - typical scenario

Site	Annual heating demands (kWh/y)	Annual electricity demand (kWh/y)	Annual cooling demands (kWh/y)	Covered heating demand by solar energy (kWh/y)	Covered heating demand by solar energy AND auxiliary electricity (kWh/y)	Covered cooling demand by RES (kWh/y)	Annual electricity production from PVGIS (kWh/y)	Energy covered ratio by RES (%)
Athens	13,648	1,019	5,484	4,456	-	1,792	4,473	53
Bergen	16,511	3,585	-	1,001	4,148	-	2,187	32
Berlin	19,084	3,380	-	2,483	5,675	-	3,001	39
Cork	17,100	1,509	-	3,118	6,716	-	1,102	42
Hamburg	19,878	3,390	-	1,942	5,610	-	2,803	36
Kimmeria	22,350	-	4,350	6,813	6,813	6,074	-	48
Krakow	25,575	3,860	-	1,506	6,670	-	3,046	33
Larnaca	9,812	1,005	6,477	3,898	-	3,242	4,680	68
Paris	10,476	3,520	-	2,663	5,186	-	3,243	60
Porto	7,946	680	-	3,413	-		4,215	88
Rome	11,146	846	1,157	3,931	-	1,286	4,245	72
Santiago	9,290	5,240	-	8,440	8,440	-	3,192	80
Sopron	4,331	3,639	-	2,854	8,088	-	2,950	303
Thessaloniki	8,973	1,955	8,520	4,205	5,915	3,199	4,220	69

4.4 Annual performance of MiniStor: Comparison between optimal and worst-case scenario

The results that have been provided thus far are derived from the worst-case scenario, which suggests that MiniStor provides satisfactory results in the most adverse conditions. Nevertheless, as previously stated, most practical applications usually start with fully charged TCM and PCM storage tanks. To that end, an optimal scenario where the discharge initiates first is also examined to demonstrate MiniStor's full capability in meeting heating and cooling demands. In this scenario, the TCM reactor is discharged at night when residential heating demand is highest, the PCM tank is discharged to meet early morning heating loads and the TCM reactor is recharged using solar heat, while a heat pump covers heating demand and simultaneously charges the PCM tank.

This strategy ensures maximum efficiency, aligning energy storage and release with demand patterns.

Due to the complexity of calculations, representative cases were chosen rather than doing a feasibility study for all selected sites. Cases including the use of auxiliary electricity and those without it were examined.

Simulations for the implementation of MiniStor in buildings located in Athens, Bergen, Hamburg, Larnaca and Rome under the optimal scenario were conducted. The heat load coverage improves from +3% up to 40%. The most significant growth is observed in Larnaca, at 40%. By discharging MiniStor at night and by taking into advantage the elevated buffer tank temperatures, the discharging/charging cycle is completed in less than a day. Athens and Rome significantly improve their coverage by 10% and 16%, respectively, under the optimal scenario. Conversely, northern cities such as Bergen and Hamburg receive minimal heat coverage improvements (2-3%) due to the greater reliance on auxiliary electricity. The heat load coverage by solar energy is constant in both cities. Therefore, the optimization strategy has the greatest impact in southern regions and a lower effect in colder climates, where auxiliary electricity supplies most of the energy to charge the TCM reactor.

A visualization of the improvement seen in Rome where the same quantities as in Figure 7 are depicted in Figure 10. The large heating load in the first night is completely covered, improving heat load coverage. If auxiliary electricity is utilized and the TCM is fully charged by the second night, the coverage could be further enhanced.
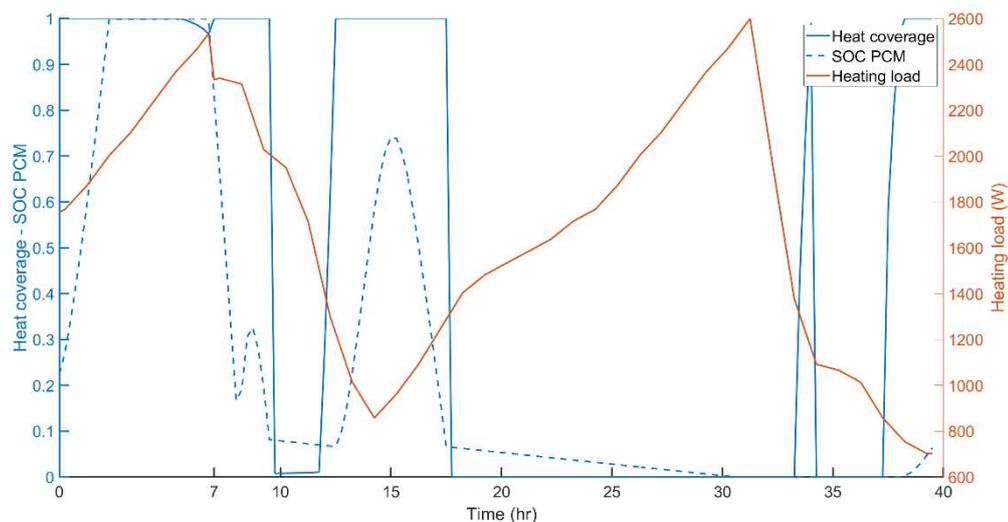

Figure 10: Heating load (W), state of charge of PCM and heat load coverage over time (hours) for the average winter period and for the building in Rome – optimal scenario

The optimal scenario for MiniStor cooling operation in Athens and Larnaca is also investigated. Discharging starts at dawn, when cooling loads increase. The cooling demands in Athens are entirely met (100%) by discharging the TCM first, followed by the cold PCM. Using this optimization technique, the cooling load coverage in Larnaca reaches 87%. The effect of the optimization is lower in Thessaloniki and Kimmeria, where cooling loads exceed Ministor's capacity to produce chilled water. Therefore, MiniStor can fully meet the cooling demands of a single-family residential building with reasonable cooling loads.

Table 14 presents a comparative analysis of the typical and optimal scenarios for MiniStor and renewable energy utilization across five different locations: Athens, Bergen, Hamburg, Larnaca, and Rome. The comparison focuses on the covered heating demand by solar energy, the total heating demand covered by solar and auxiliary electricity, the covered cooling demand by RES, and the overall energy coverage ratio by RES. The rest of the quantities (e.g., heating and cooling demand) are the same as in in Table 13.

In Athens, optimizing the system significantly increases the covered heating demand by solar energy, from 4,456 kWh/y in the typical scenario to 5,199 kWh/y in the optimal scenario. The covered cooling demand by RES shows a notable improvement, nearly doubling from 1,792 kWh/y to 3,382 kWh/y. This results in a significant increase in the overall energy coverage ratio, rising from 53% to 65%.

Bergen and Hamburg demonstrate a more modest improvement with optimization. The covered heating demand by solar energy remains constant in both scenarios. The energy covered ratio by RES improves slightly, e.g., from 32% to 34% for Bergen, suggesting that while optimization has benefits, the overall impact is less pronounced in northern location, due to their climatic conditions.

A more significant improvement is observed in Larnaca, where optimization nearly doubles the covered heating demand by solar energy, increasing from 3,898 kWh/y in the typical scenario to 7,433 kWh/y in the optimal scenario. The covered cooling demand by RES also sees a substantial increase, from 3,242 kWh/y to 6,133 kWh/y. This results in a remarkable jump in the energy covered ratio, which exceeds 100% in the optimal scenario (from 68% to 106%), suggesting that in some periods, renewable sources may generate more energy than required. Finally, Rome also benefits significantly from optimization. The covered heating demand by solar energy rises from 3,931 kWh/y to 6,100 kWh/y, and the covered cooling demand by RES increases from 1,286 kWh/y to 1,649 kWh/y. Consequently, the overall energy coverage ratio improves from 72% to 91%, indicating strong potential for renewable energy integration in this location.

Overall, the results highlight that optimization generally enhances the performance of MiniStor, with varying degrees of improvement depending on the site's climatic conditions and energy needs. Locations with higher solar potential, such as Larnaca and Rome, show the most significant gains, while colder climates like Bergen and Hamburg see more modest improvements.

Table 14: Annual heating and cooling demand coverage by RES: typical vs. optimal scenarios

Site	Covered heating demand by solar energy (kWh/y)		Covered heating demand by solar energy AND auxiliary electricity (kWh/y)		Covered cooling demand by RES (kWh/y)		Energy covered ratio by RES (%)	
	Typical scenario	Optimal scenario	Typical scenario	Optimal scenario	Typical scenario	Optimal scenario	Typical scenario	Optimal scenario
Athens	4,456	5,199	-	-	1,792	3,382	53	65
Bergen	1,001	1,001	4,148	4,720	-	-	32	34
Hamburg	1,942	1,942	5,610	6,042	-	-	36	38
Larnaca	3,898	7,433	-	-	3,242	6,133	68	106
Rome	3,931	6,100	-	-	1,286	1,649	72	91

5. Conclusions and recommendations for successful replication

This chapter synthesizes the findings from the analysis and presents a set of guidelines to support the successful replication of the MiniStor system across various regions in Europe and Mission Innovation countries with harsh climatic conditions.

The analysis conducted in this deliverable highlights several critical factors influencing the MiniStor system's installation and replication potential. The key findings can be categorized as follows:

Legislative Compliance: The use of ammonia (R717) as a refrigerant is subject to stringent regulations across the EU. Compliance with the EN 378 standard and other relevant directives is essential for safe and legal operation. Certain countries, such as Italy and France, impose stricter requirements, necessitating careful planning during installation.

Installation Challenges: Insights from the Thessaloniki pre-demo site reveal logistical challenges related to the shipment and installation of the MiniStor system, particularly due to its weight and the need for precise placement. Ensuring adequate space and preparation—such as notifying residents and arranging for cranes—can help mitigate these issues.

Replication Potential: The replication analysis identified potential sites in Europe and beyond, selecting representative building typologies. MiniStor model simulations demonstrated varying degrees of heat and electric load coverage, with higher coverage in southern European cities and greater reliance on auxiliary electricity in northern regions due to lower solar radiation. The system can meet a significant portion of annual heating and cooling demands, with the highest efficiency observed in locations with favourable climatic conditions and sufficient solar exposure. Additionally, the system shows potential for generating surplus electricity during summer operations.

For the successful replication of MiniStor the following are recommended:

o   Thoroughly review and adhere to local and EU regulations regarding ammonia use.

o   Ensure installations meet safety standards, such as maintaining a minimum 2-meter distance from buildings and exits.

o   Conduct detailed site assessments to confirm adequate space and accessibility for the MiniStor system and its components.

o   Coordinate with local authorities and residents to minimize disruptions during installation.

o   Initiate the tendering process for contractors early, particularly for public institutions, to prevent delays.

o   Customize the solar field and system components based on local climatic conditions and building requirements.

o   Increase the number of photovoltaic thermal (PVT) panels and flat plate collectors in regions with lower solar radiation, even though some reliance on auxiliary electricity may remain.

o   Utilize the MiniStor model and its corresponding MATLAB replication tool for accurate system performance simulations across different regions.

o   Ensure that simulation inputs incorporate the latest meteorological data and precise building specifications.

The MiniStor system demonstrates strong replication potential across Europe and Mission Innovation countries. The feasibility analysis indicates that the system can effectively meet heating and cooling demands, achieving:

- Nearly **50% renewable energy use**.

- An **energy net consumption reduction exceeding 40%** in regions with high solar radiation.

Since most results are based on worst-case scenario simulations (i.e., empty thermal storage at startup), the project's performance targets appear achievable even with the current TCM reactor capacity. Furthermore, by optimizing discharge cycles to align with peak demand periods, MiniStor can increase its annual coverage by over **50% in milder climates**, without requiring system modifications. However, in regions with limited solar radiation, the system remains partially dependent on auxiliary electricity, making complete self-sufficiency from renewable sources unfeasible in all conditions. Nevertheless, its ability to generate surplus electricity during summer enhances its overall contribution to renewable energy use.

It is important to acknowledge the limitations of the current analysis. The replication methodology focuses solely on individual buildings, rather than district- or city-level installations, due to legislative restrictions on ammonia usage within the MiniStor system. Additionally, the analysis relies on simulations based on average winter and summer conditions. While these provide indicative results, they may not fully capture extreme weather variations, potentially affecting the accuracy of annual performance predictions. The worst-case scenario approach (starting with empty storage) may also not entirely reflect real-world operation. A more precise annual simulation of the MiniStor system can be based on **D3.10**.

In conclusion, while there is room for improvement—particularly in ensuring consistent performance across varying climates—the MiniStor system has largely met its objectives, demonstrating strong potential for replication and wider adoption. By addressing legislative, logistical, and technical challenges, and following the outlined recommendations, stakeholders can successfully implement MiniStor in their buildings. The insights and guidelines from this deliverable aim to facilitate the broader adoption of this innovative technology, contributing to a more sustainable energy future.

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