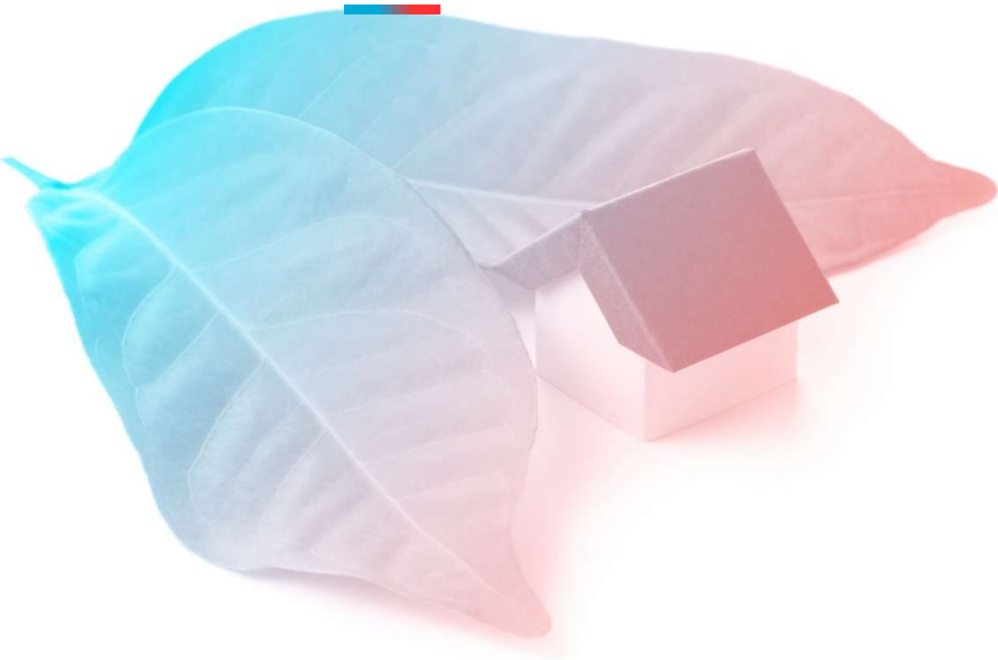
D3.10. Module to represent the system in whole-building energy modelling packages



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

D3.10. Module to represent the system in whole-building energy modelling packages

Summary

This deliverable presents the process followed to represent the thermal storage system in the energy modelling package EnergyPlus. The software was chosen as it facilitates exploring during early design stages the capabilities of thermochemical energy storage and the feasibility of the solar resource required to power it. This will lead to higher implementation by the building engineering community by representing the actual elements in different situations beyond those of the demonstration sites and for a whole year.
The plugin was developed using Python and uses lookup table techniques from data obtained during the performance testing carried out by EMI as part of T6.2. Control strategies follow those formulated by CARTIF for the prototype.
Tests were done on several variations of the Hungarian case to calibrate results. The plugin was then tested for the whole year for the demo site configurations used in the project. Results for the whole year demonstrate the difference between use of native objects and that of the plugin based on performance data with reduction of about 50% in most cases.

Deliverable Number	Work Package
D3.10	WP 3
Lead Beneficiary	Deliverable Author(S)
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Planned Delivery Date	Actual Delivery Date
31/01/2025	21/07/2025

Type of deliverable	R	Report	X
Dissemination Level	C	Confidential, only for members of the consortium (including the Commission	
	PU	Public	X

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List of Abbreviations and Acronyms

ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
API	Application Programming Interface
COP	Coefficient of Performance
DHW	Domestic Hot Water
FPC	Flat Plate Collector
HP	Heat Pump
HEMS	Home Energy Management System
HVAC	Heating, ventilation and air conditioning
PCM	Phase change Material
PLC	Programmable Logic Controller
PVT	Photovoltaic-Thermal Panels
RES	Renewable Energy Sources
TCM	Thermochemical Storage
TMY	Typical Meteorological Year

1. Introduction

This deliverable presents the process used to develop the module representing the MiniStor system in a whole-building energy modelling program. This will facilitate implementing the thermal and electrical storage in generalized settings beyond those of the demonstration sites studied within the project.

However, specific challenges are faced since current building modelling programs have problems to accurately characterize thermal energy storage, which is mostly limited to latent storage as water tanks. In many cases thermal storage is not a native object within the software. This is mainly due to the dynamic nature of other types of materials and thermal storage such as thermochemical, which require extensive computing resources to accurately represent chemical reactions and the multi-stage release and collection of heat.

Due to this reason and to provide users with results in suitable time lengths, strategies were explored to simplify the representation while not compromising on the accuracy of the results. The MiniStor project also provides opportunity for application of practical results obtained in other tasks into the programming of new modules, which were used to improve the accuracy of the potential estimation.

The use of Python as the programming language for the module also facilitates integrating new elements into existing whole-building energy modelling programs, offering possibilities to extend their capabilities by defining objects that are not native to the original program.

2. Brief introduction of the MiniStor system setup

This section provides a summary of the MiniStor system, in order to understand the components and technologies involved in its modelling representation. For a more comprehensive description, please refer to D3.1.

MiniStor is an integrated thermal storage solution designed to support sustainable heating, cooling, and electricity storage in both new and existing residential buildings. Its thermal storage capabilities are based on an advanced $CaCl_2/NH_3$ thermochemical material (TCM) reaction, complemented by PCM for storing both sensible and latent heat which are dispatched to domestic hot water (DHW) cold and heating circuits. Electrical storage utilizes a conventional Li-Ion battery system. The system enables compact storage of renewable energy generated from PVT. Additionally, MiniStor integrates a Home Energy Management System (HEMS) to efficiently synchronize and manage household energy supply and demand, responding to grid constraints and price signals.

2.1. Main Components of the MiniStor system

The MiniStor system is composed of several parts that have different installation requirements. Assembly is performed of ammonia, PCM and system control elements in the environment of a specialized factory with delivery of finished, ready-to-use units that have been tested beforehand. The solar field that starts the thermochemical reaction is installed in situ, together with the electrical battery. In this way, installation on site focuses only on preparation works, electric and hydraulic connections and internet connectivity. Key subsystems include:

a) TCM reactor containing a reactive medium ($CaCl_2$ and expanded natural graphite) and an ammonia refrigeration cycle, enabling heat storage via reversible solid/gas sorption processes, powered by an ammonia compressor. Placed inside a dedicated enclosure in a separate section.

b) A water-to-water heat pump upgrades ammonia condensation heat to higher temperatures suitable for building heating, to upgrade the heat obtained. Placed in a separate section of the dedicated enclosure.
c) PCM vessels store additional thermal energy in Phase Change Materials, with specific vessels serving heating, DHW, and cold supply functions. Placed in the same section of the heat pump.
d) PLC controller modules that enable manual and remote control of the system. Placed in the same section of the heat pump.
e) A RES-based system utilizing PVTs and solar thermal collectors for heat input, with flexibility for integration with other RES resources. Placed on a suitable area at the demo sites to maximize solar potential. Solar field controllers are placed outside the enclosure, next to the electrical storage system controllers.
f) The Electrical Energy Storage System (EESS) includes a Li-Ion battery and smart hybrid inverter for managing electricity flows between generation, storage, and consumption. Placed outdoors next or close to the enclosure and the solar field controllers.

Compliance with standards and safety requirements (such as Standard EN-378, with its full analysis performed in D2.3) defined system location, with the controlling parts and ammonia components placed in a dedicated enclosure with relevant safety systems and indicators, and the electrical battery located outdoors. The schematic system layout for the thermal part is shown in Figure 1, and detailed in D3.2. The dashed boundaries in the image indicate which elements are placed within the enclosures. Some variations exist to the basic setup, such as the additional heat pump at Santiago de Compostela (placed inside the enclosure) and the existing connections to the RES sources of demo site Kimmeria. These variations are detailed in Section 2.2.

The system is connected to the existing heating, cooling and DHW loops through insulated pipes coming from the building up to the location of the MiniStor enclosure, which are then attached to dedicated inlets and outlets located at the rear of the prototype. Examples of these connections are illustrated in Figures 2 and 3; an example of the MiniStor enclosure is shown in Figure 4. Each site has been responsible to ensure that the correct flows and pressures are maintained to reach the system and to complete the necessary loop bypass.

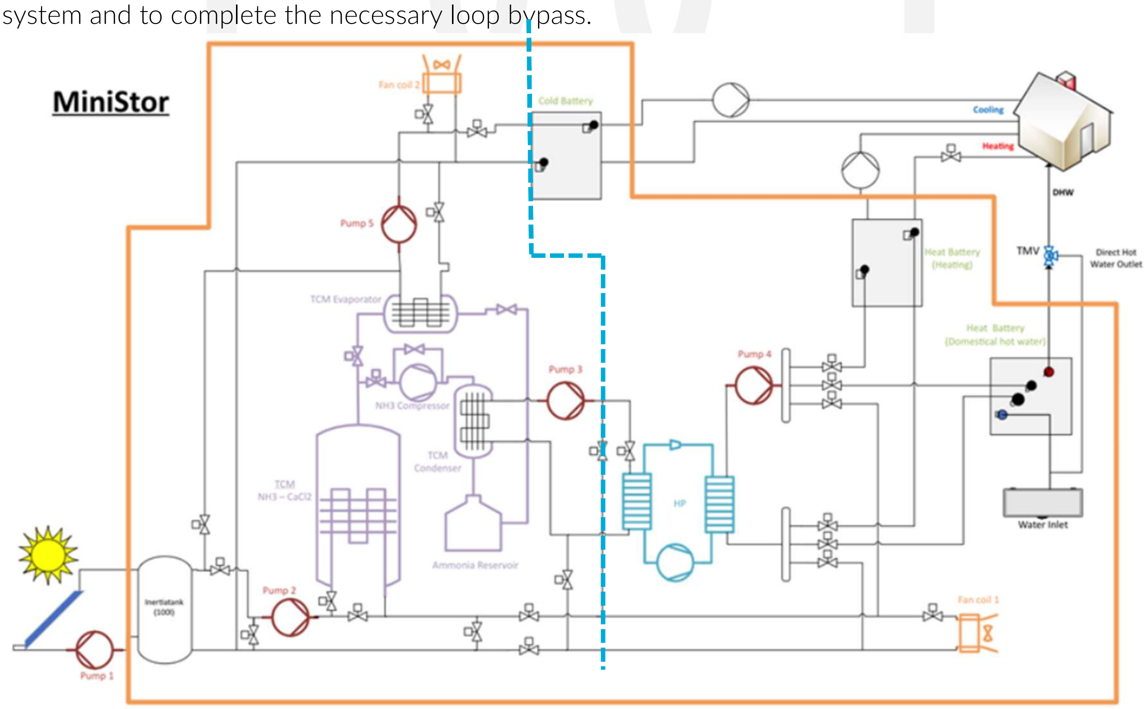

Figure 1 Final schematic thermal layout of MiniStor (source: D3.2 "Design of peripheral thermal equipment") with dashed line indicating schematic location of elements in separated enclosures

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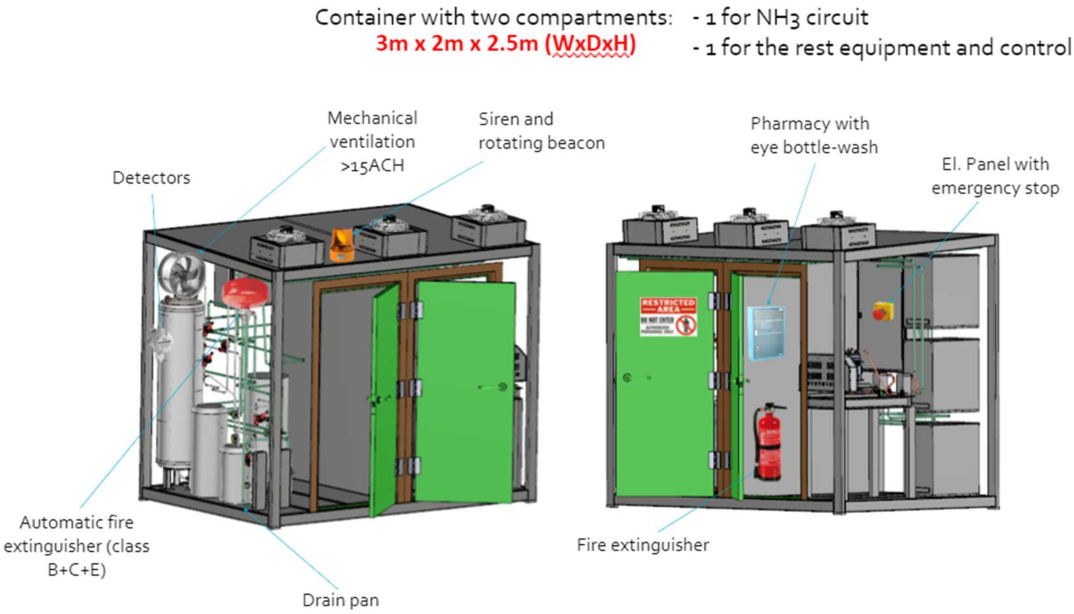

Figure 2 Three-dimensional view of machinery room for the MiniStor prototype including safety equipment. For illustration purposes the diagram does not show the opaque metal walls enclosing the system.

Ammonia tank compartment (left side) Controllers, HP and PCM compartment (right side).

Figure 3. Interior views of the two compartments of the MiniStor system in a finished prototype.

Figure 4. External view of the prototype entrance doors (left) and back side with pipe connections (right)

Figure 5. View of the glazed PVT panels for the pre-demo site in Thessaloniki

2.2. MiniStor system features specific for each demo-site.

Certain modifications to the main prototype or solar field were produced, to test alternatives (e.g. variations in the PVT panel) or to adapt to local conditions (e.g. 2-phase electrical supply in Cork and enclosure size that fits inside shipping containers). Figure 5 shows a photograph of the solar field designed for the pre-demo site in Thessaloniki, Greece, as an example of the panels laid out in rows. In the case of Cork, the solar field was placed on a special structure as a single row to save space. Variations relevant for energy modelling are summarized in Table 1:

Table 1. Variations in MiniStor features according to demonstration sites that can be relevant for energy modelling

Demo site	New Solar field	Additional Heat pump	PVT type	Electrical storage
Thessaloniki, Greece (pre-demo)	Y	N	Glazed	Y
Kimmeria, Greece	N (use existing)	N	n/a	N
Santiago de Compostela, Spain	Y	Y	Unglazed	Y
Sopron, Hungary	Y	N	Glazed	Y
Cork, Ireland	Y	N	Glazed	Y

2.3. Thermal energy generation and storage

This section describes in a simplified way how heat is generated and stored in the system through its different components, and how the thermal storage is used within the existing buildings for thermal loads.

The system is expected to provide heating, DHW and cooling as a supplement to the overall heating and cooling needs of the building, harnessing energy from renewables for later use when they are most needed. Figure 6. shows a diagram of the TCM unit that was developed.

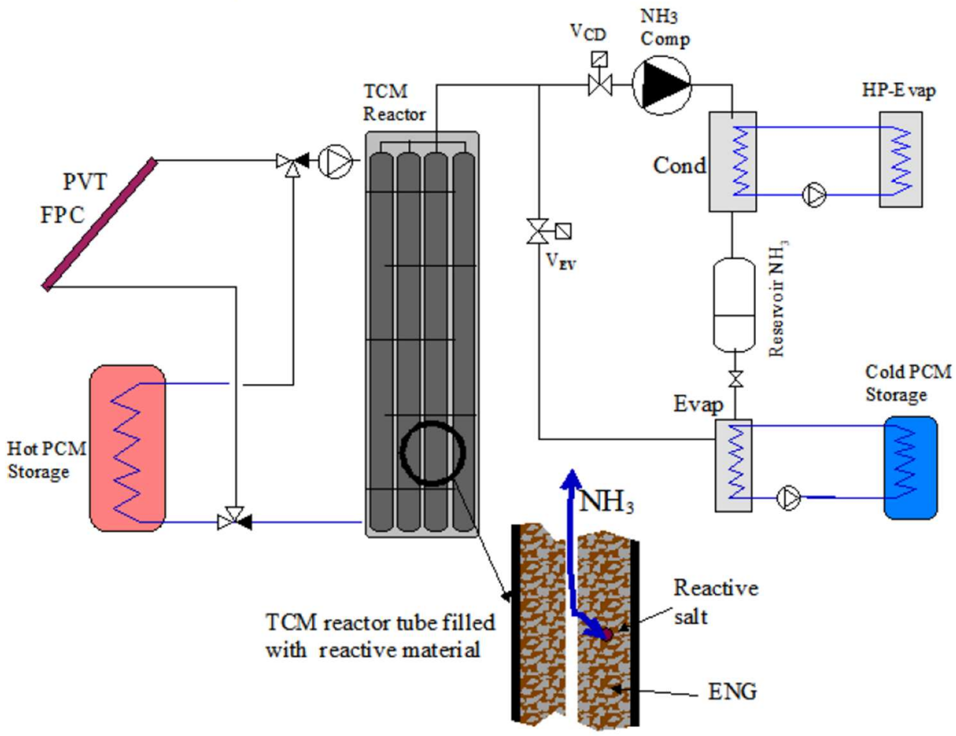

Figure 6. Diagram of TCM storage unit implemented in the MiniStor system

As such, the thermal capacity of the storage is fixed to a maximum which is dependent on the volume of salts, ammonia gas allowed, capacity of the PCM storage, and desired output temperature (which in this case is 60 °C, making it suitable for use in most residential systems). Energy for the reaction is obtained from renewable sources (RES), which in all cases is collected via the PVT panels and solar collectors into an inertia tank, until it reaches 70 °C. Backup electrical resistances inside the inertia tank are available in case the solar resource is not enough to heat the tank. The hot water from the tank is used to start a reversible TCM reaction with the heat stored in the reactor. The reaction can be done two times, in order to maximize the heat extracted from the interaction between salts and NH_3. Therefore, the rate of heat generated within the TCM reactor is not linear. On average, the full reaction can take up to 7 hours. Operation modes in the prototype allow to use the heat at different levels of completion.

Heat from the TCM reactor is transferred via water circuits to a heat pump, which upgrades and deposits heat in the PCM tanks. Cold is generated as part of the NH_3 condensation and is sent directly to a cold PCM tank. This cold PCM is optional and is dependent if there are cooling loads required. This cold PCM can be connected to water-based cooling, for example. Extra heat is dissipated to the atmosphere via fans.

Separate PCM tanks are used for DHW and heating purposes, allowing independent operation of both as required. The heat is dispatched as required to help meet a desired setpoint in the heating system, for example.

If the solar resource is enough, there is also an option for a direct “solar to PCM” storage mode, where the system charges directly the PCM.

3. Choice of whole-building energy modelling program for development of the module

Currently there is a large number of whole-building simulation programs, which analyse building performance for several aspects related to energy, daylighting, human comfort, environmental impact, etc [1] [2]. For the purposes of this report, focus will be made on three leading ones: EnergyPlus [3], TRNSYS [4] and Dymola (Modelica) [5], as they are able to model a wide variety of bespoke components. Considerations will be made on the degree of openness of their code, adaptivity to external interfaces or additions, and accommodation of novel technologies. Account will also be made of the tools used to perform specific system calculations for its dimensioning.

3.1. System dimensioning calculations made during the project and prototype manufacture

Early during the project, calculations were made to dimension the system [6] using specialized performance and chemical reaction software such as ASPEN PLUS and ASPEN DYNAMICS [7] for the thermochemical part, heat pump and ancillary equipment, and transient system modelling such as TRNSYS for the PVT thermo-electrical and control aspects, using MATLAB [8] integration for several of these models. Detailed results of these calculations can be found in D3.1.

However, dimensioning modelling of the system is extremely detailed and time consuming, in some cases taking days to complete. Calculations were made for specific representative periods (extreme and average) of three days in summer and three days in winter for each of the demonstration sites, considering heating and cooling degree days for the base temperature. Weather data was taken from Typical Meteorological Year (TMY) files, with some of these files generated by Meteonorm [9], and in the case of Kimmeria supplemented with solar radiation files from the PVGIS database of the Joint Research Centre (JRC). Physical characteristics were based on the actual demo site buildings. Heating and cooling loads for summer and winter correspond to several standardized methodologies such as ASHRAE and EN 12831:2017 applied to the representative set of days. This led to determination of the number of PVT and FPC panels required in each location to produce and maintain the TCM reaction temperature. Electrical profiles including electrical price signals were based on data provided by the demonstration sites.

The dimensioning calculations ensure that the system can work under the specific thermal and electrical demands of the demonstration sites. After these calculations, specifications were made of off-the-shelf equipment and devices to be used based on the model availability of that time. The calculations also defined physical measurements and specifications for manufacturing the TCM reactor, which was carried out by partner Sofrigam (France) and integrated by Psyctotherm in Greece for delivery to the demo sites. Bespoke PVTs, off the shelf FPCs, batteries and solar electrical components were provided, shipped and installed by ENDEF directly to the demo sites.

3.2. EnergyPlus

This software was initially developed under the leadership of Lawrence Berkeley Labs and the Department of Energy in the US as a successor to some of the first whole-building simulation programs such as BLAST and DOE-2. It has been validated extensively and grown over time to become an open-source collaborative effort under responsibility of the US National Renewable Energy Laboratory (NREL) with several researchers and engineers worldwide helping its continuous development [10].

The software code is open source, and its builds are free for download. Redistribution and modifications to the source code are allowed as long as the copyright notice is displayed [11]. These facts and its open-source nature has encouraged a large body of research to be performed using this software, including the representation of new technologies that are not included in its core libraries. Its modularity makes suitable for use with co-simulation and extensions without the need of modifying the source code, further facilitating modelling research. Interaction with the Python programming language is based on the native objects of the "energy management system", short lines of codes that interact with the software to add new functionalities without using Python.

As long as the modeller has access to an exhaustive list of features required by existing objects within the software, EnergyPlus is relatively agile for analysis of several configurations at different design steps, including using conceptual HVAC systems that are useful to apply when building design is at the early stages and for parametric simulations. One setback, however, is that technical support is limited, which in practice can add more time to the development of co-simulation or programming methods. Ample documentation and some user fora are available online. EnergyPlus does not have an interface and is run from the command line, although the software compilation team provides a simple pre-processor during distribution, since the creation of independent interfaces is encouraged.

3.3. TRNSYS

This software is paid, proprietary code and uses a graphical interface to "drag and drop" components and connect to each other. It focuses on assessing the performance of thermal and electrical energy system. It has two parts: one is the solver for thermophysical properties, databases and equations. The other is the library of "components", which defines several whole systems, such as buildings, HVAC equipment, etc and how they behave, such as schedules. These libraries can be edited according to the needs of the user. Support is provided by the vendor for existing libraries.

This tool is more suitable for design of systems based on known elements, but less for research analysis such as parametric simulations. Co-simulation is not frequently used with TRNSYS as it can be done through independent development of library types, which are compiled within the program. Real-time applications using TRNSYS are available, such as optimization for system controllers such as PLCs [12].

3.4. Dymola (using the Modelica open language)

This is another commercial tool based on the open Modelica modelling language. It is also based on libraries containing information on the specific components according to the domain for modelling. It has both an equation-based solver and graphical interface that similar to TRNSYS, also connects the simulation components at a high-level.

It offers connectivity to other software via the Functional Mock-up Interface (FMI) and Python programming language. Its use for building simulation is mostly for the design of whole systems such as HVAC units, with bespoke components needing definitions through the equation solver.

3.5. Python as binding language for new objects - API

Python is a programming language that has become highly popular as it allows extensibility via modules that can communicate and add functionalities to existing applications via Application Programming Interfaces (APIs) [13]. These modules are colloquially called "plugins". This can be done by adding self-contained code that interacts with a given application to achieve an action, or through software libraries written in Python language that perform code for a given objective (e.g. solver for chemical processes) that is separate from the main application.

The existence of specialized libraries creates the potential to develop own code that, if done correctly, can be close to that of established stand-alone applications. However, to achieve this, accuracy of results must be tested, and code maintenance must be done frequently. At the same time, interaction between libraries from different origin is not guaranteed.

It is important for the target software to allow communication with Python APIs, which makes interaction of this with the plugin to be preferable than using several libraries as a stand-alone routine.

3.6. Choice of software for plugin implementation

Due to the features described in the previous sub-sections, EnergyPlus was chosen as the target software for plugin implementation. The API documentation can be followed by programmers without having knowledge of the software. At the same time, it is suitable for large-scale calculations such as annual, monthly and building stock simulations [14] which is of interest to represent the system in a wider array of use settings and for purposes such as feasibility studies and early stage design.

4. System simplifications and representation techniques for plugin integration

4.1. Choice of simplification approach

In order to represent adequately the system in a variety of geographical and usage situations, balance must be made between level of detail required by the chosen whole-building modelling program, the level of calculation performed, and assumptions made based on available initial information. This means that a “grey box” approach (in contrast to black and white box approaches) [15] must be used, where some elements are to be represented in full detail, while others to serve as proxy to the more complex ones.

Software limitations for representing new elements were identified and solutions proposed how to overcome them. In our case, the exclusive use of water as heat storage medium in EnergyPlus was addressed by identifying key components (PVT and solar collectors, inertia tank and heat exchangers) that can be represented in detail using native objects within EnergyPlus, and characterization of novel heat storage elements (TCM reactor + PCM tanks) through suitable equivalent objects such as water heaters, pumps and heat exchangers, whose behaviour can be adapted to the simulation needs while maintaining the integrity of the equations.

Table 2 below summarizes the mapping between the physical components of the MiniStor system and the proxy EnergyPlus objects used to represent their behaviour within the simulation environment. This approach ensures that novel subsystems such as thermochemical and phase change storage are appropriately simulated without requiring major modifications such as writing entirely new objects, which can be time consuming and requires validation out of the scope of the representation module.

Table 2. Correspondence between physical components of the MiniStor system and their proxy representations in Energy Plus

MiniStor Component	Proxy in EnergyPlus	Notes
Solar Field (PVT + FPC)	Solar Collector: FlatPlate + Solar Collector: Photovoltaic Thermal	Modeled using native solar thermal collector objects
Inertia Tank	Thermal Storage:Stratified	Connected upstream of TCM unit to maintain 70°C outlet temperature
TCM Reactor+ PCM Storage (DHW & Heating)	Water Heater + Plant Loop Heat Exchanger	Input/output temperatures from performance data mapped at actuator level.

		PCM configure to maintain 60°C outlet temperature
Internal Heat Pump	Efficiency modelled via Pump:VariableSpeed + Setpoint Manager	Used to simulate heat upgrade process

Co-simulation with specialized chemical processes software (e.g. Aspen) was considered, as well as the use of python libraries of the same subject. The first option was discarded as standalone modelling in chemical processes software can extend for several hours, due to the complexity of calculations. This fact makes it unsuitable for feasibility analysis as parameters undergo several changes during the early design stages. The second option was limited by its reliance on specialised libraries, which may lack sufficient robustness in their implementation. This can introduce potential programming issues derived from incomplete features or incompatibilities.

4.2. Use of performance testing to represent thermal storage

The selected approach was to incorporate performance data from the prototype itself to the modelling, which has been used for similar purposes to rate novel and complex thermal storage systems [2]. The MiniStor performance tests were carried out in the context of T6.2 by partner EMI (Hungary), which focused on functional and quality acceptance testing. These tests verified the unit's functionality before deployment to the demonstration sites. Results of these performance tests are used to substitute them in physically logical interaction points during the simulation, where they serve as input for the rest of the energy balance equations. EnergyPlus allows such data substitution only in specific points of the calculation process, using data that can be processed by its native objects. This keeps modelling results realistic and avoids equation manipulation.

Performance testing methods and results are described in detail in D6.2, but relevant aspects from it are mentioned here. These tests measured heat output and electrical consumption of the entire unit under charging and discharging conditions. Due to the novelty of the storage, which has outlets for heating, cooling and DHW, a test rig was designed for this purpose (Figure 5 and Figure 7). In it, solar heated water was substituted with water heated at controlled temperatures to trigger charging and discharging cycles of the unit, for winter and summer conditions. Loads were simulated through heat exchangers circulating water in a circuit. Measurements were taken every 3 minutes at the inlets and outlets, and every minute from the prototype's internal monitoring system which was made available to its data cloud. Results from the performance testing are summarized in Figure 8 for temperature output during the performance testing, and in Figure 9 for power used.

Figure 7 View of the performance testing rig at EMI facilities for physical modelling of the prototype

From the point of view of the thermal storage user, the system will guarantee an output of 60 ˚C for DHW and heating systems, which is adequate to prevent legionellosis. However, total energy consumption of the prototype varies according to operation mode in use (for example, from solar field direct to PCM, or if the heat pump was used). The operation mode used at a given point in time during testing was recorded in both measurement systems.

Despite the integration effort, it is important to acknowledge that EnergyPlus is not inherently designed to model solid-gas thermochemical reactions. Therefore, the use of performance-based lookup tables serves as a pragmatic compromise that allows researchers to simulate the expected outputs of TCM storage without solving detailed reaction kinetics. This makes the plugin especially suitable for early-stage design, feasibility studies, or building stock analysis, where simplified but realistic energy behaviour is preferred over exact chemical fidelity.

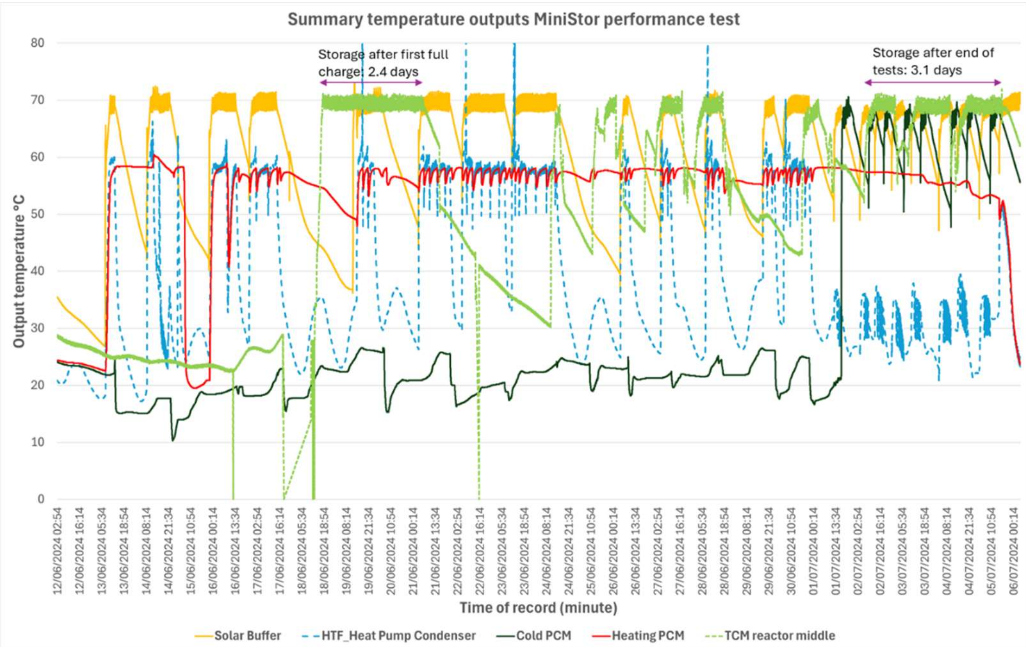

Figure 8: Summary of temperature outputs from MiniStor during performance testing

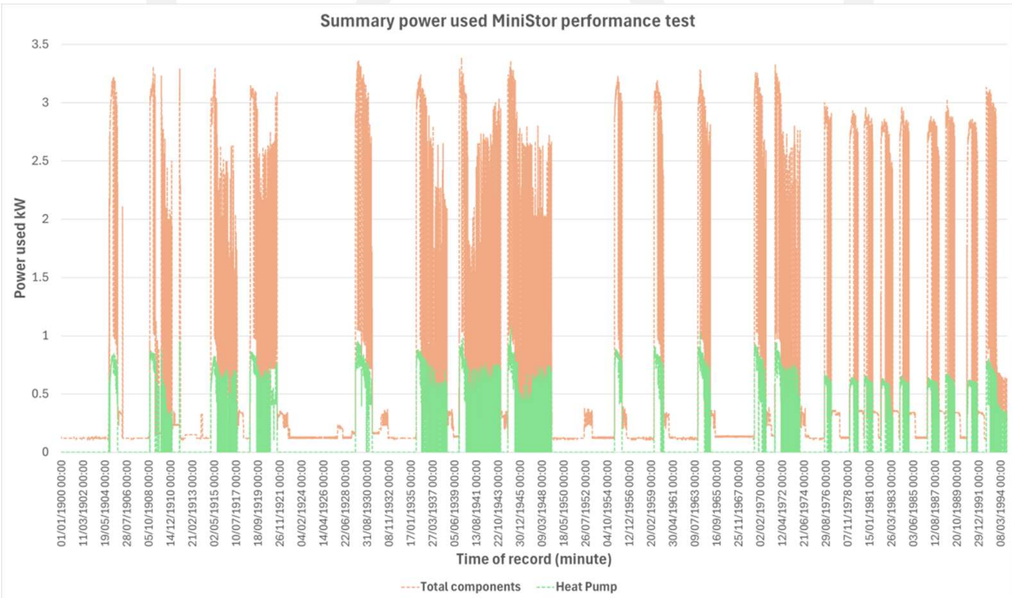

Figure 9: Summary of power used in the MiniStor system during performance testing

5. Implementation of the Python plugin for EnergyPlus

To effectively emulate the operation of the MiniStor system for modelling, the plugin algorithm must dynamically evaluate the state of solar energy availability, storage readiness, and thermal demand. The goal is to replicate decision-making logic that would occur in a real deployment, switching between modes such as direct solar-to-PCM charging, TCM-based thermal discharge, or backup heating activation based on conditions. These modes were derived from observed prototype behaviours during lab testing and reflect realistic system operation logic. Figure 10 shows the methodology workflow that was followed to represent the MiniStor system.

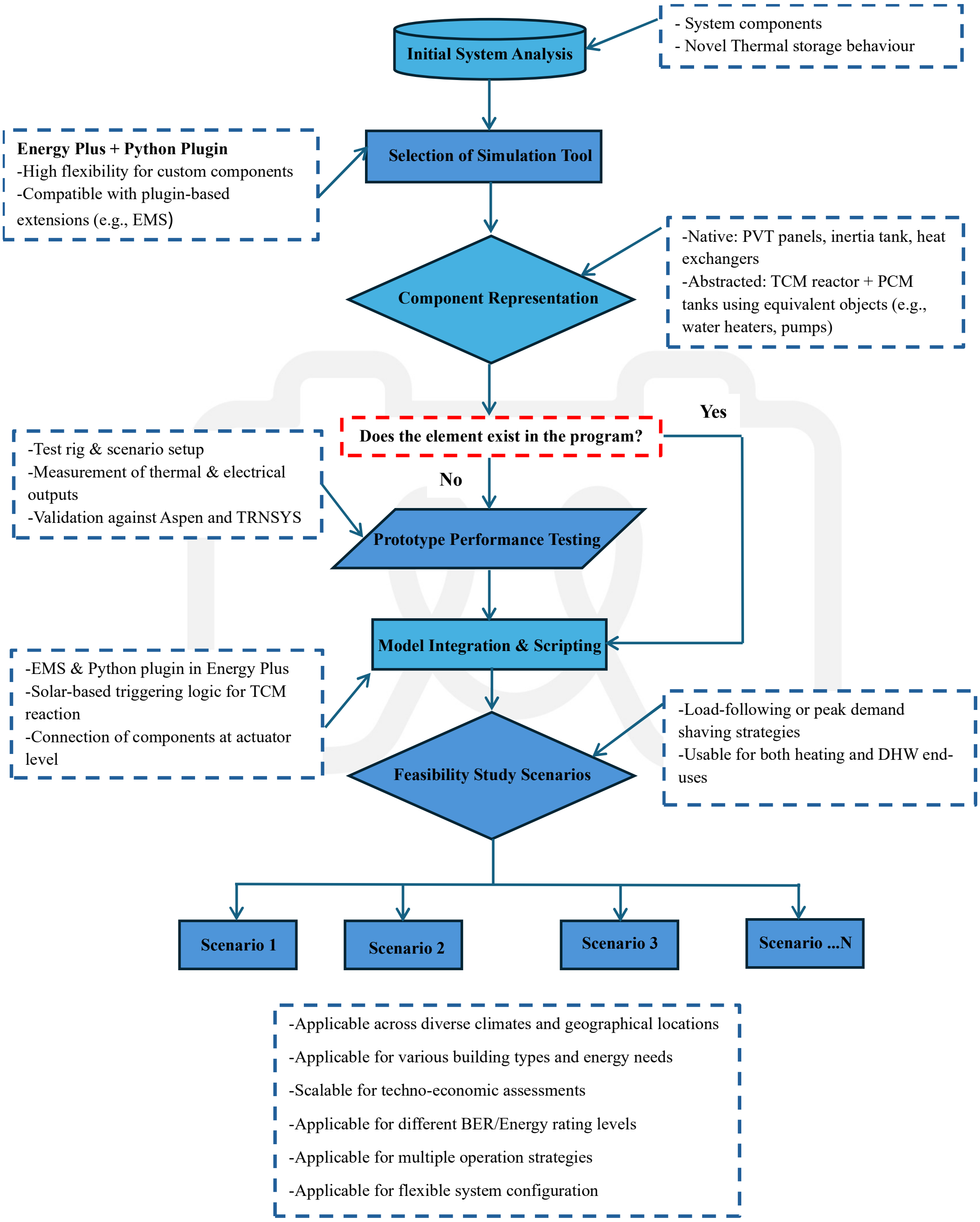

Figure 10. Methodology Workflow for representing the MiniStor System

5.1. Algorithm definition

The sequence of instructions to implement adequate data substitution was based on how the thermal storage system works as installed in the demonstration sites. The algorithm verifies if solar thermal energy stored in the inertia tank as produced by the local solar resource (flat plate collectors and PVTs) is enough to trigger the TCM reaction at 70 °C.

If the condition is true, the corresponding operation mode (direct heating or upgrade through heat pump) is selected according to the amount of time the heat has been kept. The output temperature values as measured from the tests are correlated at the actuator level of the heat exchangers, and for efficiency at the pump level to correspond with the measured electrical consumption of the whole system.

Substitution of the values should correspond to those from the tests according to a table that correlates the values. Timesteps of 10 minutes should be used in order to correspond with the recommended timestep values in the simulation program to avoid the simulation process becoming unstable [3]. The 10-minute simulation timestep was chosen after iterative testing, as it offered a balance between simulation stability and fidelity in capturing the transient thermal response of the TCM reaction cycle. Smaller timesteps (e.g., 1-5 minutes) led to significant increases in modelling runtime without proportionate gains in accuracy, while using larger timesteps (like 15–30 minutes) made the results too smooth and caused the model to miss significant changes in how the system work.

If the initial condition is not true, this would activate the electrical backup heater to guarantee supply, and the corresponding output values would be used. Figure 11 presents simplified flowchart of the decision-making algorithm in the MiniStor plugin.

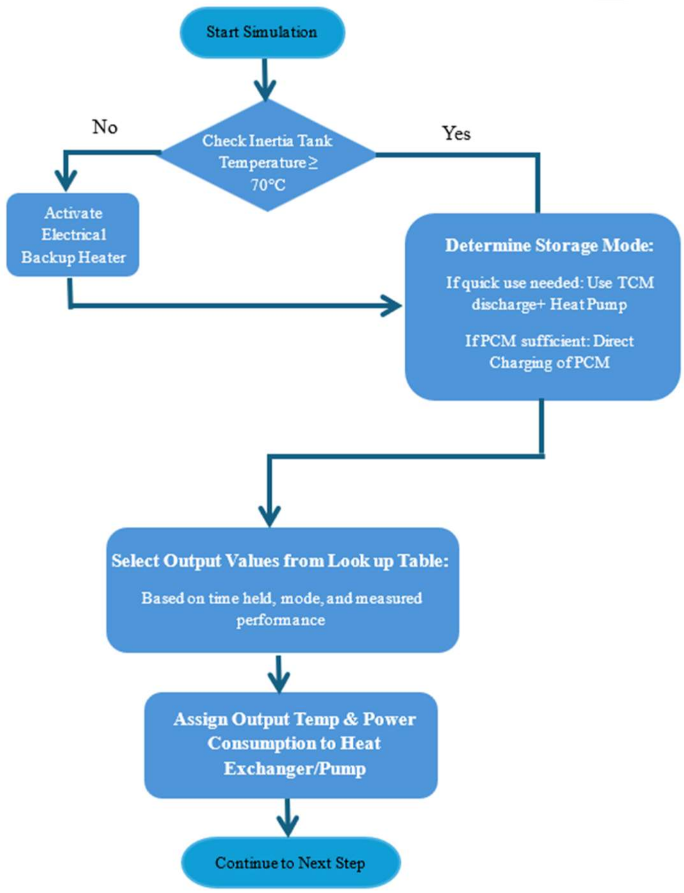

Figure 11. Simplified flowchart of the MiniStor plugin decision-making algorithm

5.2. Preparation of input file, performance data and plugin coding

A base input file for EnergyPlus (extension .idf) was prepared using DesignBuilder [4] based on the requirements outlined in Section 4, using electric water heaters with electricity in the modelled building to compare the fuel factors (heating loop and DHW loop, right side of the Figure). The diagram representing the file is presented in Figure 12. The input file assumes that the target building has separated circuits for heating and DHW. If required, the target building circuits could be changed for gas boilers or heat pumps, for example.

These circuits are connected via heat exchangers (blue rectangles in the Figure) to the MiniStor system (thermal storage and solar loop, left side of Figure). The solar loop follows the main features of the actual solar field and inertia tank, while the thermal storage loop is used as proxy for the TCM, ammonia circuit, internal heat pump and PCM components[1]. The figure shows in yellow the node and actuator points considered for substitution or tracking the supply and demand inlet and outlet nodes, and in orange the tracking node for the solar inertia tank. These loops are also powered by electricity. The MiniStor system is used as a water pre-heater in both cases.

The building area and its features (e.g. schedules, equipment, wall composition, etc) can be varied according to the needs of the simulation. Flow values are based on different standards (e.g. Irish and British standards on minimal domestic piping mass flow rate) but which are applicable to different locations.

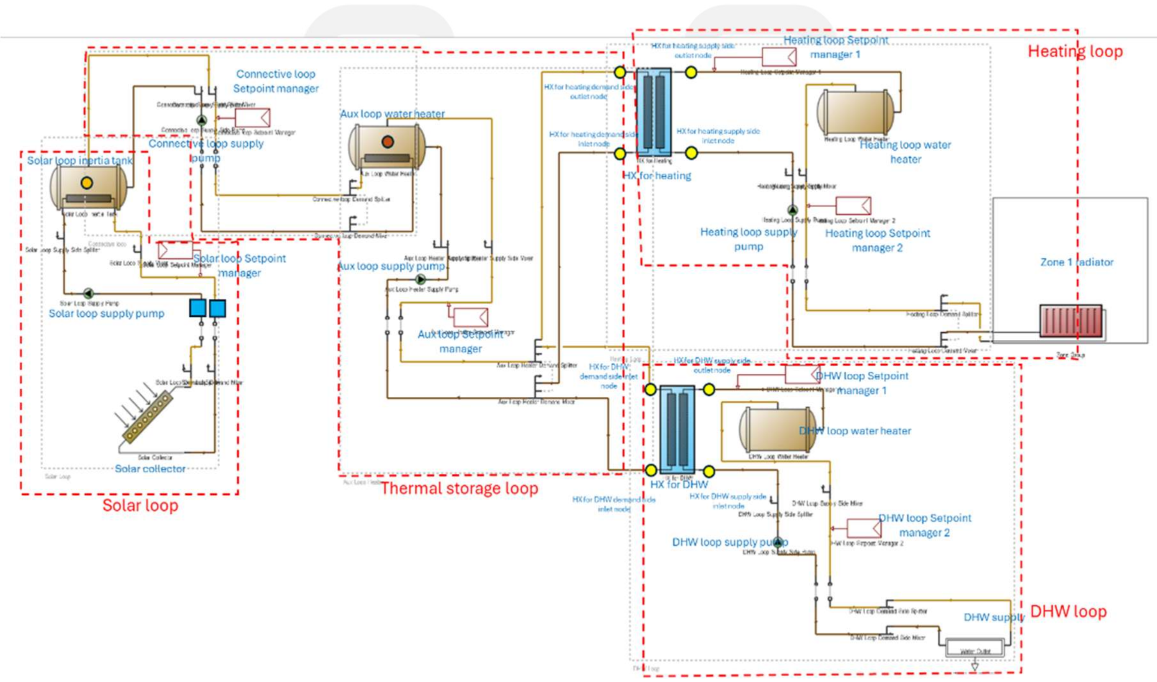

Figure 12. System abstraction in EnergyPlus for use with the Python plugin

5.2.1 EMS calling points

Interaction with many (but not all) native objects within the EnergyPlus simulation, is done through “sensors”, “actuators”, and “calling points”. Sensors are used to obtain the value of a variable, actuators can produce an action (e.g. turn on or off) or use a given value, and calling points are the restricted events where these actions can take place in order to safeguard calculation integrity.

[1] While we recognise that specifying material types in the design is important, the implemented workflow uses a more generic yet consistent approach to model the system's components.

EnergyPlus interacts with these through the "Energy Management System" (EMS), an internal language to introduce "smart functioning" features. Unfortunately, the documentation does not provide comprehensive explanations on the best calling point to apply according to the situation. Therefore, a trial-and-error approach was used, until the most suitable components and their actuators were found. In some cases, even if the calling points were invoked, there was no interaction and those were discarded. Excessive calling points increase simulation times significantly.

The suitable calling point found for this case was *on_inside_hvac_system_iteration_loop*. The tracked variable for the inertia tank is the *Water Heater Tank Temperature*, and for the heat exchangers is *Plant Component HeatExchanger:FluidToFluid*. Energy usage was calculated from the average pressure rise for the system and from the heat pump by itself.

To meet the requirements for the plugin to actuate during the simulation for several cases, data from both the internal monitoring system and the performance tests underwent a statistical characterisation process to obtain typical days, making it usable for the required yearly calculation period in several locations. Identification in the files was made of the corresponding performance tests (solar to PCM, solar to TCM and HP, use of backup heater) to produce the respective data points for use with look up tables.

The algorithm was coded in Python and is accessed via a batch file (.bat) that invokes EnergyPlus. The file specifies the .idf and weather file (.epw) to be used. The .idf file in turn also has an object with the name of the plugin that must be accessed.

5.2.2 Simulation run times with the plugin

The plugin was run several times to test it and verify the results. Run times are highly dependent on the processor, available memory and model complexity. Simple models can take 7-10 minutes to run on a contemporary i7 processor, while complex models can take up to 45 minutes.

6. Results from the Python plugin

6.1. Description of the test building and weather files

The plugin and idf file have been designed to be used for almost any type of HVAC system and plant configuration that can accept a fluid-to-fluid heat exchanger. To examine the plugin, a basic building was used that was adapted for each of the cases to reflect the demonstration sites as well as other types of buildings.

The basic building had variable window and wall materials to obtain the envelope U-value. It was first tested on the demo site of Sopron, Hungary with several variations to calibrate the plugin. It was then modified and tested for the sites Thessaloniki and Kimmeria – Greece; Santiago de Compostela – Spain; and Cork – Ireland. Building features used for each of the modelled cases are based on data from D6.4 and D3.1, while the solar field size, array of solar collectors and PVT model follow the calculated values for each site.

Except for Thessaloniki, all weather files were generated using Meteonorm [5] which is considered a reliable software for this purpose. The Thessaloniki weather file was downloaded from the EnergyPlus website repository. The process involved generating in Meteonorm *historic* EnergyPlus weather files. This is different from the process followed in D3.1, which used *future* weather files based on specific climate change scenarios. The rationale for this is that historic weather files would be the type most accessed by consultants performing feasibility studies to install thermal storage (e.g. these are the ones available in the EnergyPlus repository for all locations).

6.2. Results of modelling base case with and without plugin

This section presents the modelling results for the five demo site locations. Table 4 and Figures 12 to 16 compare multiple scenarios, including the base case, systems with water-based thermal storage (no plugin), and the full MiniStor setup. For consistency, electricity consumption values in both the Table and Figures are normalised per floor area. These results allow us to assess the impact of system enhancements and control strategies on energy performance under different climatic conditions. For reference, when thermal storage is mentioned, it includes also the solar field.

For the case of Sopron, several modelling calibration tests were conducted before applying the plugin to all the demonstration sites. The test building was first varied according to the energy performance rating of Hungary. Modelling with and without thermal storage was made in both a "D"-rated and a highly insulated home (i.e., the energy rating of the house as is, and the project case with better thermal performance), in order to verify if adding the MiniStor system produced a change in the energy consumption and its extent. There was also a preliminary test to define the effect of increasing the PVT area in the "D"-rated home on the performance of the thermal storage itself to see if results changed due to increased availability of solar resource.

Table 3. Summary of results for each demo site by scenarios of evaluation

		Heating [kWh/m²]	DHW [kWh/m²]	Solar electricity produced [kWh/m²]	Thermal Storage energy use [kWh/m²]	Thermal storage final consumption [kWh/m²]	Solar water production [kWh/m²]	Total [kWh/m²]
HU SOPRON	1: Base case (D-rated house)	97.6	55.0	0.0	0.0	0.0	0.0	152.6
	2: Water-based thermal storage (no plugin)	5.9	11.3	25.7	132.4	106.7	29.1	123.9
	3: Base case (D-rated) + MiniStor	64.2	3.4	25.7	32.4	6.6	24.9	74.2
	4: Base case (D-rated) +MiniStor+ double PVT area	64.1	3.5	49.5	32.5	-17.1	60.0	50.5
	5: Improved U-value (uprated) – base case in project	50.3	55.0	0.0	0.0	0.0	0.0	105.2
	6: Improved U-value (uprated) + MiniStor	26.3	3.3	25.7	32.0	6.3	24.8	36.0
IE CORK	1: Base case	108.2	54.0	0.0	0.0	0.0	0.0	162.2
	2: Water-based thermal storage (no plugin)	1.6	6.1	22.6	153.3	130.7	19.8	138.4
	3: Base case + MiniStor	65.1	0.9	22.6	36.2	13.6	15.7	79.5
HL KIMMERIA	1: Base case	97.5	50.0	0.0	0.0	0.0	0.0	147.5
	2: Water-based thermal storage (no plugin)	4.5	26.5	34.0	114.1	80.0	56.8	111.1
	3: Base case + MiniStor	60.7	12.4	34.0	29.5	-4.5	52.8	68.5
ES SANTIAGO	1: Base case	101.5	51.8	0.0	0.0	0.0	0.0	153.3
	2: Water-based thermal storage (no plugin)	4.9	22.1	29.4	125.7	96.3	42.5	123.2
	3: Base case + MiniStor	62.9	8.7	29.4	31.6	2.2	38.0	73.7
HL THESSALONIKI	1: Base case (	99.9	48.7	0.0	0.0	0.0	0.0	148.6
	2: Water-based thermal storage (no plugin)	99.9	45.8	33.6	5.9	-27.7	63.2	117.9
	3: Base case + MiniStor	99.9	45.8	33.6	51.6	17.9	59.5	163.6

Table 4 together with Figures 12 to 16 illustrate the scenarios (along the y-axis) with their cumulative electric consumption (in x-axis), for each of the demo sites. To gain some degree of comparability, the y-axes are normalised per floor area. Thermal storage final energy consumption refers to the assumption that all electrical energy produced in the solar field is used by the system, either as consumption (positive values) or excess (negative values).

Sopron, Hungary

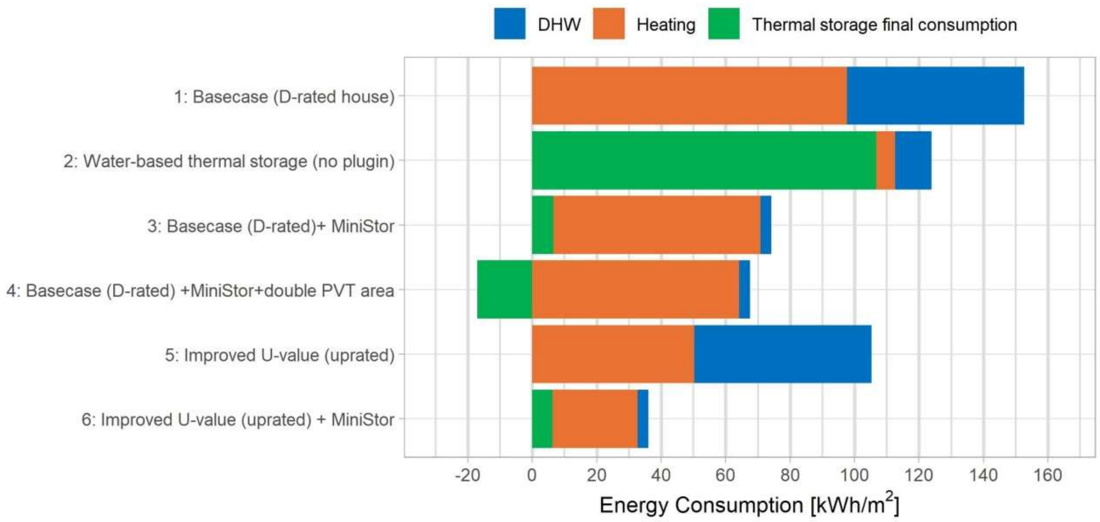

Figure 13. Modelling of thermal storage with water-based system and with Python plugin using TCM performance test values for Sopron, Hungary

Figure 13 illustrates the demo site located in Sopron, Hungary. The leftmost bar shows the base case scenario, which serves as the benchmark for comparison with the following ones. This bar is divided into heating (approximately two-thirds of the total) and domestic hot water. Each system is assumed to operate at a nominal efficiency of 90%. It should be noted that equipment efficiency has been considered identical for all demonstration sites.

The second bar represents the presence of the water-based thermal storage, although operating in a sequential non-optimised mode, that is, without the plugin that manages the optimal (and more realistic) operation of the MiniStor system.

While the inner processes of the water-based storage system demonstrate a roughly one-fifth reduction in electricity requirement with respect to the base case, it must be noted that because the plugin is not implemented in this scenario, the storage tank operates very inefficiently. Most of the energy is used by the water-based thermal energy storage, which in this scenario cannot be covered by the installed solar resource.

The third bar represents the effect of a fully operating MiniStor system using TCM storage with the values from the performance testing. The reduction of electricity surpasses 50%. Contrary to the second scenario, the PVTs achieve covering a significant amount of electricity used by the TCM storage system, resulting in an immediate reduction.

The fourth bar illustrates a proof-of-concept scenario where the surface area of the solar field (both PVT and solar collectors) is doubled, with the aim of covering the electricity that is still required in the third bar. As expected, the total electric requirement of the thermal energy storage decreases compared to the third scenario, producing an excess. Any surplus electricity is shown as a negative value. The heating output remains nearly unchanged, which could be attributed to the fixed capacity of the thermal storage. Depending on local regulations and site conditions, the electricity excess could potentially be sold to the grid or used internally, offering economic benefits in addition to reducing energy demand.

The fifth bar compares the A-rated home, which corresponds to the demo case in Sopron, without the application of MiniStor. The results are in line with the expected values compared with the D-rated home, with heating reduced by nearly 50% relative to the base case, maintaining the same requirement for domestic hot water.

The sixth and bottom bar shows the effect of a fully implemented MiniStor system, akin to the third scenario. Compared to the base case, the reduction is over three-quarters of the electric requirement, however, compared to the improved envelope (scenario 5), the reduction is of about 65% which is relatively higher than the reduction found in scenario 3. Such an improved reduction is typical of modern low-enthalpy technologies, which operate more efficiently when the insulation of the building is high.

<u>Cork, Ireland</u>

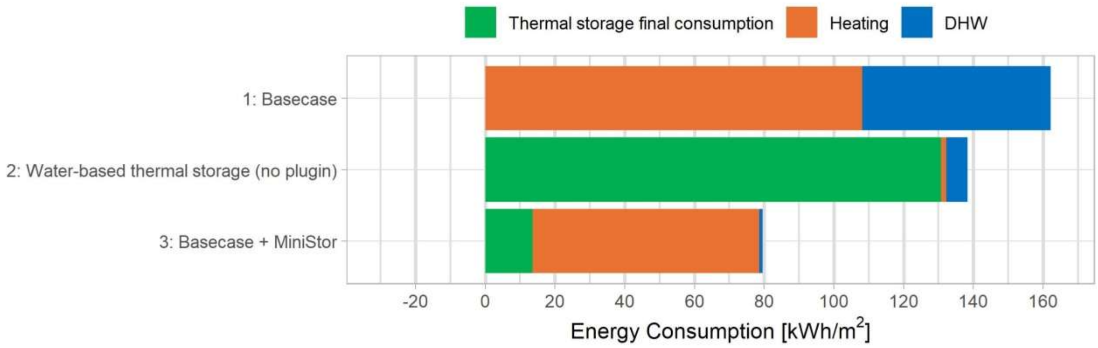

Figure 14. Modelling of thermal storage with water-based system and with Python plugin using TCM performance test values for Cork, Ireland

Figure 14 illustrates scenarios for the demo site in Cork City, Ireland. The top bar represents the base case scenario. The bar is split between heating (about 67% of total) and domestic hot water (the remaining 33%).

The presence of a water-based thermal storage (system without plugin, represented in the second bar), reduces the total amount of electricity by about 15%, even though most of this is used by the water-based thermal storage configuration (as highlighted in green). The installed solar field cannot cover this energy requirement.

A fully operating MiniStor system (represented in the bottom bar) reduces the total amount of electricity by just above 50%. Due to the dispatching of thermal energy and the temperate weather, the requirement of electricity for domestic hot water is nearly removed in full.

<u>Kimmeria, Greece</u>

Figure 15 illustrates scenarios for the demo site in Kimmeria, Greece. The top bar represents the base case scenario, without thermal energy storage of any kind. The bar is split between heating (about 66% of total) and domestic hot water (the remaining 34%).

The presence of a water-based thermal storage, (no plugin), reduces the total amount of electricity in about 25%. In this scenario, the requirement for heating is reduced by nearly 95%, whereas domestic hot water is reduced by 47%. However, electricity consumption from the water-based thermal energy storage is a significant item.

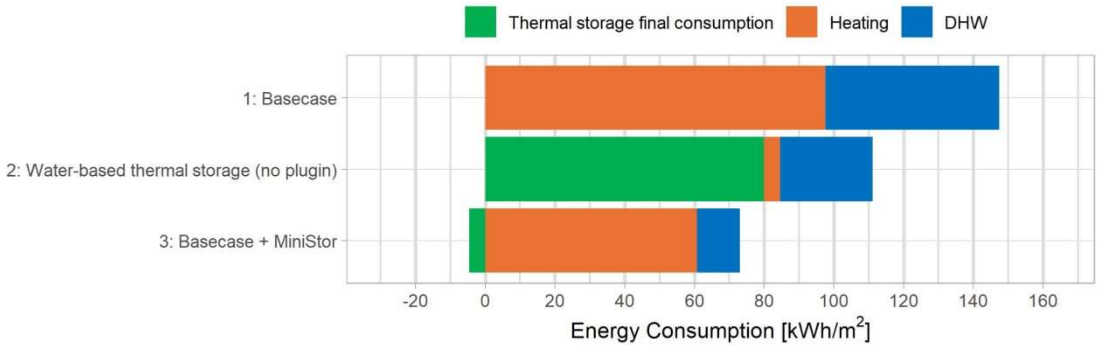

Figure 15. Modelling of thermal storage with water-based system and with Python plugin using TCM performance test values for Kimmeria, Greece

A fully operating MiniStor system reduces the total amount of electricity by more than 50%, however, some exceedance of electricity is reported (highlighted in green, around 5 kWh/m2). It must be remembered that this site has an extensive solar field, so the savings could be higher using the site's solar field management system.

Santiago de Compostela, Spain

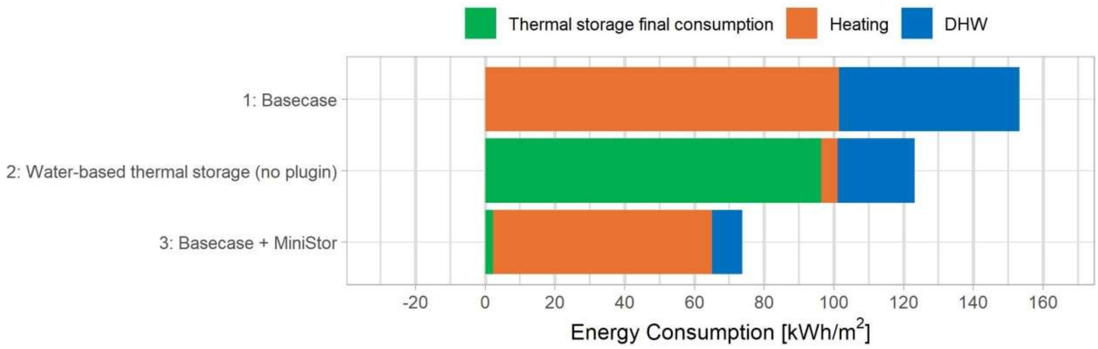

Figure 16. Modelling of thermal storage with water-based system and with Python plugin using TCM performance test values for Santiago de Compostela, Spain

Figure 16 illustrates the scenarios for the demo site in Santiago de Compostela, Spain. For the base case scenario, the bar is split between heating (about 66% of total) and domestic hot water (the remaining 34%).

The presence of a water-based thermal storage reduces the total amount of electricity by about 20%. Similar to the Kimmeria site (in Figure 14), the requirement for heating is reduced by nearly 95%, whereas domestic hot water is reduced by 38%. The amount of electricity required by the storage heater taking over the operation in this scenario represents 78% (highlighted in green).

A fully operating MiniStor system reduces the total amount of electricity by more than 50%.

Thessaloniki, Greece

Figure 17 illustrates scenarios for the demo site in Thessaloniki, Greece. For the base case scenario, the bar is split between heating (about 67% of total) and domestic hot water (the remaining 33%).

The presence of a water-based thermal storage does not reduce the heat demand but reduces domestic hot water energy consumption. However, it contributes to the overall energy balance by generating surplus electricity, shown in green in the negative section of Figure 16. This surplus accounts for approximately one-fifth of the total energy consumed. One potential explanation is that the building has already very high performance.

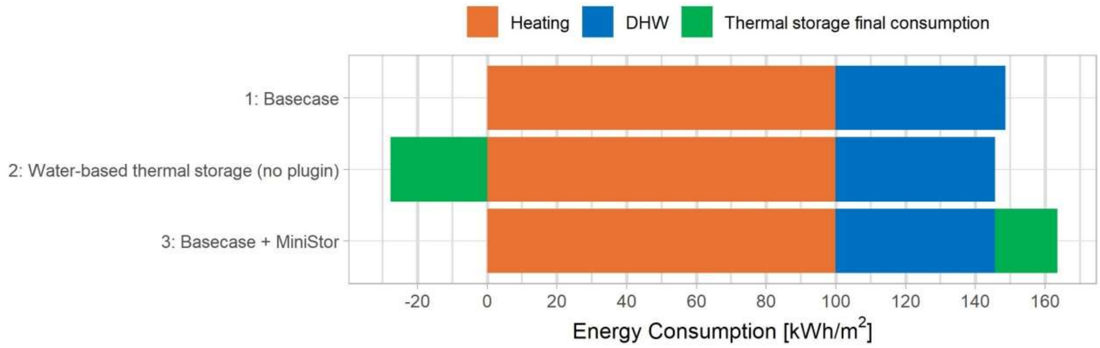

Figure 17. Modelling of thermal storage with water-based system and with Python plugin using TCM performance test values for Thessaloniki, Greece

For the scenario with a fully operating MiniStor system there is a slight increase in electricity consumption from operating the thermochemical system itself. The effect of a potentially oversized system for an already well-performing building is more significant here. The same capacity thermal storage was used in all demonstration sites, while in the real demonstration further operation modes were implemented to supply exactly what is needed. This outcome is common for low-enthalpy technologies using heat pumps when the system capacity is too large. To prevent this, it is important to carefully assess heat loss and system performance during the design phase, ensuring the correct capacity is chosen and prioritising energy demand for different services.

It must be pointed out Thessaloniki is located in a coastal Mediterranean climate (and to be more accurate, the weather file refers to the Thessaloniki Airport Makedonia[2] data). This is different from Kimmeria, which is also a good energy-performing building, but is located more inland (with a mountain influence, according to its weather file[3]). Using a single size thermal storage capacity in the modelling, the system is suitable for climates where winter imposes a higher heating demand. Advanced thermochemical energy storage can help both good and low performing buildings, but better performing buildings benefit the most from this storage due to their higher insulation levels, improved comfort, etc.

The next steps would be to correlate the cooling tests for the Greek sites to characterise the thermal storage performance for building cooling, which for that climate can present higher requirements than heating.

[2] World Meteorological Organization Station 166220, 40°31.4287′N, 22°58.5819′E, 7m amsl
[3] Produced by Meteonorm, 41°8.3999′N, 24°54.5995′E, 58m amsl

7. Conclusions

The technique presented in this report allows extending calculations made during the dimensioning stage of the project from a few days to the whole year, providing improved predictions of MiniStor performance. The use of EnergyPlus as a widespread modelling tool also facilitates the application of the plugin by several types of practitioners.

Data obtained to produce the estimate uses actual performance data from the thermochemical storage unit as a whole and allows to estimate its benefit in locations and configurations beyond those of the project demo sites. This provides input for designers when incorporating thermal energy storage during early design phases. The run times for obtaining results are also considerable reduced compared to chemical process simulation. Operation modes were similar to those applied on the working unit.

For this report, the plugin directly connects to rather idealised building abstractions associated to each location. Nevertheless, more detailed HVAC settings can be modelled, increasing the plugin usability and impact to help analyse a broader range of buildings, geometries and strategies as done for the variations to calibrate results. Future steps will also include modelling cooling storage, which is also a feature in MiniStor, and which is of higher importance for demonstration sites located in the Mediterranean area.

The presented results, obtained through the plugin, demonstrate that MiniStor effectively meets overall energy requirements, as well as those of its individual components. On average, MiniStor reduces the requirement of electricity for the demonstration sites as abstracted in the deliverable reports by about 50%. Even when the control strategies are disabled, the combination of a water-based thermal storage and solar technology reduces an average of 20% with respect to the base case scenarios.

In sites and times with higher levels of solar radiation, or where the availability of solar resource can be increased, some exceedance of electricity can be expected. This reinforces the objectives of having electrical storage together with thermal storage, where subject to the country-specific restrictions, exceedance can be fed into the grid, with the corresponding energetical, environmental and economic benefits.

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