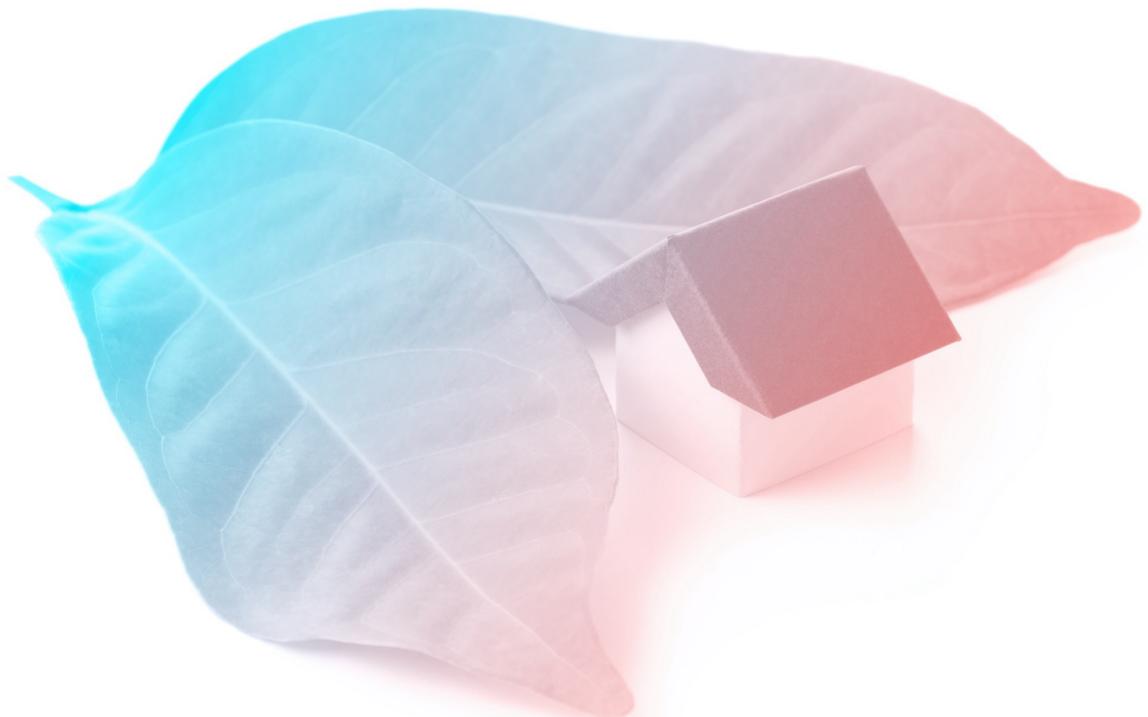




Second report on KPI measurement and analysis



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Summary

This report presents the final evaluation of the 49 Key Performance Indicators (KPIs) defined for the MiniStor system. The assessment is based on monitoring data from all five demonstration sites, complemented by simulation results where measured data were unavailable. The KPIs cover technical, environmental, economic, and user-related aspects, reflecting the holistic objectives of the MiniStor project.

Overall, the results confirm the system's technical feasibility and its potential for improving energy efficiency and integrating renewable sources in residential buildings. Notably, significant thermal energy savings and high user satisfaction were observed across multiple sites.

However, some KPIs—especially those related to long-term economic performance and life cycle metrics—could not be completely met, primarily due to the prototype status of the system (TRL 7) and limited operational data. These limitations are transparently discussed.

The analysis demonstrates that MiniStor is a promising and scalable approach for low-emission heating and cooling. It also highlights areas for improvement in future system versions, particularly regarding cost reduction, standardisation, and long-term performance monitoring.

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1. Introduction

The MiniStor project (Minimal Size Thermal and Electrical Energy Storage System for In-Situ Residential Installation) is funded under the European Union's Horizon 2020 research and innovation programme. Its central objective is to develop and demonstrate a compact and modular thermal and electrical energy storage system for residential buildings. MiniStor aims to contribute to the decarbonisation of the European building stock by enabling the flexible use of renewable energy sources, enhancing energy efficiency, and reducing greenhouse gas emissions. The system integrates thermal storage technologies based on phase change and thermochemical storage materials, coupled with photovoltaic-thermal (PVT) energy harvesting and intelligent control strategies.

Following the system development and laboratory validation stages, the MiniStor prototype was installed and operated at five demonstration sites located in Ireland, Spain, twice in Greece, and Hungary. These sites were selected to reflect a range of climatic conditions and building typologies, thereby supporting technical validation and market replication potential. The demonstration phase was accompanied by an extensive monitoring campaign, providing the empirical basis for the evaluation of the system's performance in real-life conditions.

This report (Deliverable D6.6) presents the final outcomes of Task 6.5 "KPIs measurement & analysis" in work package 6. It builds upon the monitoring framework and KPI definitions established in Deliverable D6.1 and complements the initial KPI analysis presented in Deliverable D6.5. The aim of this report is to provide a comprehensive review of all Key Performance Indicators (KPIs) determined for the MiniStor system, based on the monitoring and simulation data generated based on the laboratory measurements.

For each KPI, the following elements are presented:

- The KPI definition,
- calculation method and formula,
- calculation based on measurement or simulation data,
- discussion of results in the context of system operation and site-specific conditions.

Where applicable, results are presented for all relevant demonstration sites. Limitations regarding data availability, sensor reliability, or operation timeframes are clearly identified and discussed. Particular attention is given to the comparability of pre- and post-installation conditions, to ensure a robust and transparent assessment.

2. Review of Key Performance Indicators (KPIs)

This section provides an encompassing evaluation of the Key Performance Indicators (KPIs) for the MiniStor system. The purpose of this assessment is to determine the extent to which the MiniStor solution has met the quantitative and qualitative targets set out in Deliverable D6.1.

Table 1: Overview of all 49 Key Performance Indicators (KPIs) defined in the MiniStor project. For each KPI, the corresponding objective or threshold is listed (if applicable), along with the final assessment outcome based on available data. The last column provides references to the relevant sections of Deliverable D6.6 or other related deliverables (e.g. D6.5) where detailed calculations, data sources, and further explanations can be found.

KPI No.	KPI Title	Goal	Result	Assessment outcome	Related information
KPI_1	System volume of TCM	< 0.6 m ³	0.082 m ³	Compliant	D6.5
KPI_2	System volume of hot PCM (HW)	–	58.82 L	Evaluated	D6.5
KPI_3	System volume of hot PCM (DHW)	–	29.41 L	Evaluated	D6.5
KPI_4	System volume of cold PCM	–	58.14 L	Evaluated	D6.5
KPI_5	System volume overall (TCM + PCM)	< 0.72 m ³	0.228 m ³	Compliant	D6.5
KPI_6	Permissible outdoor temperature range	-20 to +50 °C	Minimum: -8 °C Maximum: +39.8 °C	Compliant	D6.5
KPI_7	Overall storage density	182 kWh/m ³	133.1 kWh/m ³	Non-compliant due to scaled system operation	D6.5
KPI_8	TCM storage density	205 kWh/m ³	212.3 kWh/m ³	Compliant	D6.5
KPI_9	Required electric power for heat pump	< 1 kWe	< 1 kWe	Compliant	D6.5
KPI_10	PVT efficiency boost	+5 % efficiency	Glazed PVT: -2.5 % Unglazed PVT: +8.5 %	Compliant	D6.5
KPI_11	Absolute thermal energy savings	–	Up to 26.4 kWh/day	Evaluated	Page 11
KPI_12	Overall coefficient of performance	> 1.8	1.81	Compliant	Page 13
KPI_13	Relative change in thermal energy net consumption	≥ 40 %	Up to 315 %	Compliant	Page 16
KPI_14	Energy losses	–		KPI excluded in the revision of D6.1	Page 18
KPI_15	RES on-site average use	50 %	Up to 81.61 %	Compliant	Page 19
KPI_16	Visualisation of retrofit design options	Likert ≥ 4.5 / 5		Not calculatable	Page 21
KPI_17	Electrical energy savings	< 0 % (reduction)	Reduction up to 3.7 %	Compliant	Page 22
KPI_18	Change in electrical consumption from grid	–	Reduction up to 2.2 kWh/day	Evaluated	Page 24
KPI_19	Share of renewables	Maximise	Up to 91 %	Evaluated	Page 28
KPI_20	Self-electricity production / self-sufficiency ratio	Maximise	Up to 89.5 %	Evaluated	Page 30
KPI_21	Max. hourly energy surplus / deficit	–		Not calculatable	Page 32
KPI_22	Expected lifetime	> 20 years	Up to 25 years	Compliant	Page 33

KPI_23	System reliability	–	Up to 65 %	Evaluated	Page 34
KPI_24	User acceptance	> 95 %	100 %	Compliant	Page 35
KPI_25	Thermal comfort reported by users	> 95 %	172 %	Compliant	Page 36
KPI_26	Change in perceived thermal comfort	–		Evaluated	Page 37
KPI_27	Users involved in dissemination	≥ 1000	48'550	Compliant	Page 40
KPI_28	Compliance: NH ₃ usage & storage	Pass	Pass	Compliant	Page 41
KPI_29	Compliance: Container as machinery room	Pass	Pass	Compliant	Page 42
KPI_30	Compliance: Planning regulations	Pass	Pass	Compliant	Page 43
KPI_31	Reduced fossil fuel consumption	-25 % (target)	Reduction up to 315 %	Compliant	Page 44
KPI_32	Reduction of GHG emissions	< 31.87 kg CO ₂ eq/m ² /year	16.96 kg CO ₂ eq/m ² /year	Compliant	Page 45
KPI_33	Total capital cost per kW installed	–		Not calculatable	Page 46
KPI_34	Reduction in construction costs	-20 %	At best 0 %	Non-compliant due to prototype stage TRL7	Page 47
KPI_35	Operational cost (€/kWh)	–	0.022 €/kWh	Evaluated	Page 49
KPI_36	Payback period	≤ 6.7 years		Non-compliant due to prototype stage TRL7	Page 51
KPI_37	Reduction of energy cost	-30 %	Reduction up to 100 %	Compliant	Page 52
KPI_38	Internal Rate of Return (IRR)	–	Up to 14 %	Evaluated	Page 54
KPI_39	Return on Investment (ROI)	–	Up to 69 %	Evaluated	Page 55
KPI_40	Maintenance cost reduction	> 25 %		Not calculatable due to prototype stage TRL7	Page 57
KPI_41	Maintenance frequency reduction	> 20 %		Not calculatable due to prototype stage TRL7	Page 58
KPI_42	Energy cost savings in demo sites	-30 %	Reduction up to 315 %	Compliant	Page 59
KPI_43	Reduction of energy consumption	> 25 %	Reduction up to 315 %	Compliant	Page 60
KPI_44	Energy storage costs (€/kWh)	–		Not calculatable due to prototype stage TRL7	Page 61
KPI_45	Energy Return on Investment (EROI)	–	Up to 37.5	Evaluated	Page 62
KPI_46	Cost of downtimes	–		Not calculatable due to prototype stage TRL7	Page 63
KPI_47	Life-cycle cost of energy storage	–		Not calculatable due to prototype stage TRL7	Page 64
KPI_48	Total annual costs	–	2550 €/year	Evaluated	Page 65
KPI_49	Annuity Gain	–	Up to 831 €	Evaluated	Page 66

KPI_1 System volume of TCM

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_2 System volume of hot PCM (HW)

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_3 System volume of hot PCM (DHW)

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_4 System volume of cold PCM

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_5 System volume overall (TCM + PCM)

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_6 Permissible outdoor temperature range

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_7 Overall storage density

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_8 TCM storage density

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_9 Required electric power for heat pump

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.

KPI_10 PVT efficiency boost

A detailed description, calculation methodology, and analysis of this KPI are already included in the revised version of Deliverable D6.5 "Initial Report on KPI Measurement and Analysis." As the content remains valid and unchanged, this note is provided here for completeness and easier reference.



KPI_11 Absolute thermal energy savings

KPI description

Change of thermal energy consumption to satisfy the heat/cooling demand of the building normalised with respect to different climatic conditions (weather influence) and usage influence (change of the number of inhabitants). The energy consumption is calculated over 6 months or the longest possible comparable period in which the MiniStor system is running respectively not running.

Formula for calculation

$$KPI = (Q_{before} - Q_{after})$$

Q_{before} energy consumption of building's heating/cooling system before MiniStor is installed/operational.

Q_{after} energy consumption of heating / cooling system when MiniStor is operated (during a comparable period compared to Q_{before}).

(KPI_11 is closely related to KPI_13 as being the absolute difference compared to the relative difference)

Results

The scatter plots compare thermal energy consumption before and after the installation of the MiniStor system. Each data point represents one monitoring period. The pairing of the periods before and after the installation of the MiniStor system is described in the next paragraph. The x-axis shows the energy demand during the reference period (before MiniStor), while the y-axis shows the energy consumption during operation of the MiniStor system. The size of each point indicates the duration of the operation period in days, and the colour reflects the average outdoor temperature during the respective interval. The dashed line ($y = x$) indicates unchanged consumption; values below the line represent thermal energy savings.

The assessment of KPI_11 is based on a period-wise comparison of thermal energy consumption before and after the installation of the MiniStor system. In a first step, all time intervals during which MiniStor was operating for at least one day were extracted. For each of these active periods, a corresponding reference period from the previous year was identified, following these matching criteria:

- The reference period must have the same duration (± 10 min) as the active MiniStor period,
- The average outdoor temperature must fall within a tolerance range of ± 0.2 °C,
- The reference period must be located approximately one year earlier, with a maximum deviation of ± 30 calendar days, and
- The MiniStor system must not have been installed or operational during the reference period.

This matching procedure ensures a high degree of comparability between pre- and post-installation conditions, allowing the observed differences in energy consumption to be attributed primarily to the operation of the MiniStor system.

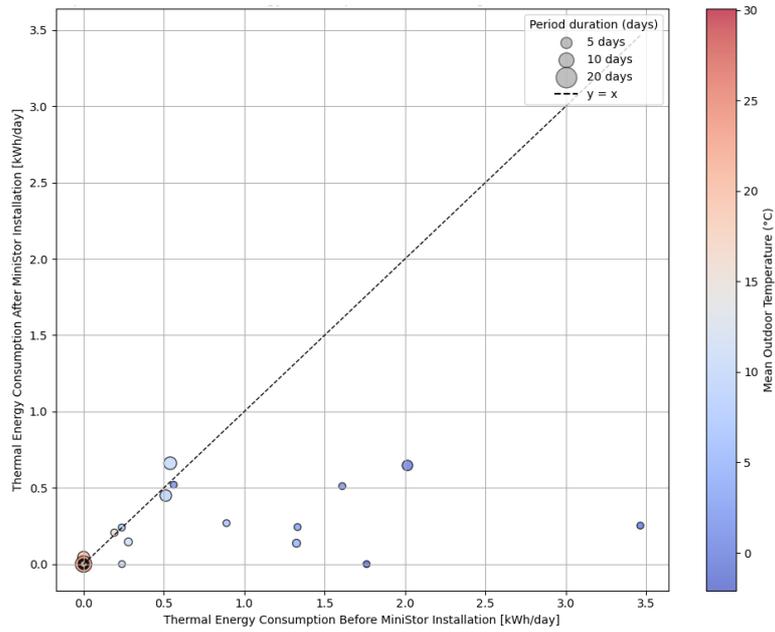


Figure 2: Sopron – Comparison of thermal energy consumption before and after MiniStor installation. Number of active periods: 28 (of which 13 showed no thermal energy consumption and were excluded from the calculation). Average absolute thermal energy saving: 0.71 kWh/day.

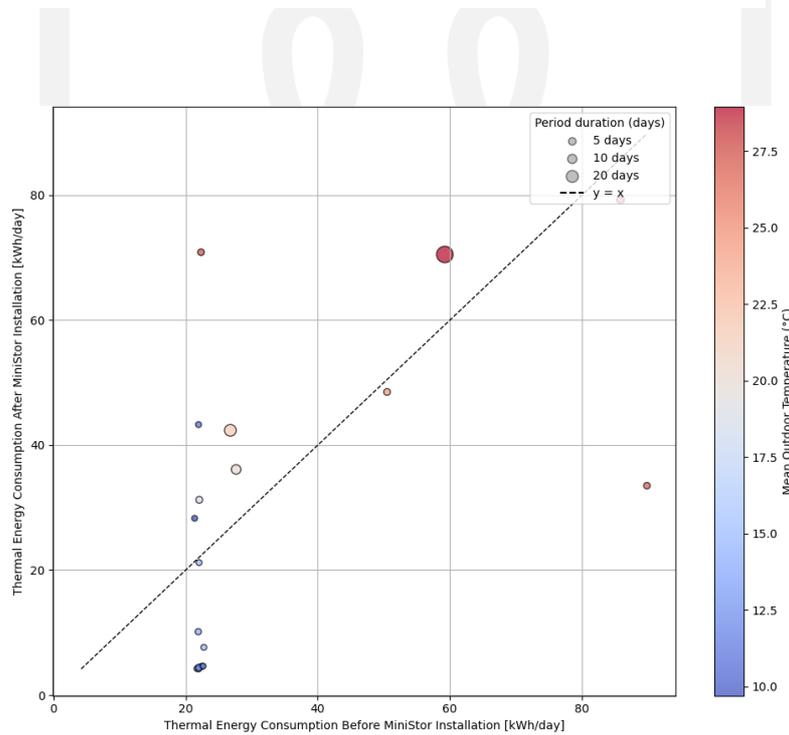


Figure 3: Thessaloniki – Comparison of thermal energy consumption before and after MiniStor installation. Number of periods: 18. Average absolute thermal energy saving: 3.33 kWh/day.

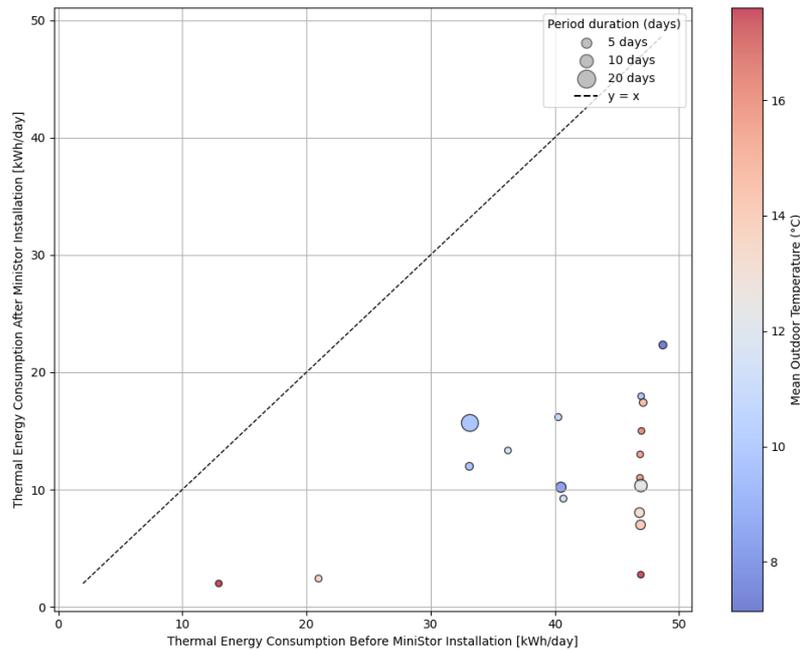


Figure 4: Santiago de Compostela (USC) – Comparison of thermal energy consumption before and after MiniStor installation. Number of periods: 18. Average absolute thermal energy saving: 29.1 kWh/day.

Table 2: Overview of absolute thermal energy savings (KPI_11) at all demonstration sites. The table summarises the number of evaluated periods and the resulting average absolute thermal energy savings per day.

Demo Site	Count: Active periods	Mean absolute energy saving (measured)	Mean absolute energy saving (simulated)
Cork	–	–	26.4 kWh/day
Kimmeria	–	–	20.5 kWh/day
Santiago de Compostela	18	29.1 kWh/day	22.5 kWh/day
Sopron	28 (-13)	0.71 kWh/day	23.4 kWh/day
Thessaloniki (pre-pilot)	18	3.33 kWh/day	–

Discussion

The analysis of KPI_11 includes measured data from two of the four active demonstration sites (Sopron and Santiago de Compostela) as well as the pre-pilot site in Thessaloniki. For the Cork and Kimmeria sites, no validated measurement data were available at the time of reporting. In Cork, a compressor malfunction prevented stable operation of the MiniStor system during the intended monitoring phase. In Kimmeria, the thermal energy meter failed, rendering the collected data unusable. For all sites except Thessaloniki, simulated thermal energy consumption data—derived from performance models and laboratory validation—were used to estimate the expected absolute energy savings. In the case of Thessaloniki, no conclusive simulation results could be obtained.

All three sites with measured data show clear and quantifiable thermal energy savings. In Santiago de Compostela, high absolute savings were observed due to both consistent system operation and substantial thermal demand. In Thessaloniki, savings were measurable but less pronounced, which can be attributed to elevated outdoor temperatures during most monitoring periods. As a result, heating demand was limited and the MiniStor system had few opportunities to actively contribute to thermal load coverage.

In Sopron, the average daily energy savings based on measurements were also relatively modest. This outcome is not the result of poor system performance but rather reflects the very low thermal energy consumption observed during the active periods. In many intervals, the building had negligible thermal energy demand, thus limiting the technical potential for measurable reductions. This observation is further supported by the relative performance analysis in KPI_13, where Sopron achieved substantial percentual savings, confirming that MiniStor contributed significantly during the limited period.

Overall, measurable thermal energy savings were observed at all evaluated sites. The absolute value of these savings varies according to seasonal boundary conditions and the corresponding thermal demand. Sites with active MiniStor operation during colder periods achieved higher absolute savings, while those monitored during warmer conditions showed limited but still positive results. The simulation-based values generally support the measured data and provide a useful indication of performance potential under idealised conditions.

Despite these positive findings, it must be emphasised that the number and duration of valid monitoring periods remain limited. In several cases, active MiniStor operation was short, and the dataset per site was insufficient for a solid statistical analysis. The results presented here should therefore be regarded as indicative. A more conclusive assessment would require extended monitoring campaigns across full heating and cooling seasons, with continuous and fault-free system operation.

KPI_12 Overall coefficient of performance

KPI description

The coefficient of performance (COP) indicates how much electrical power is required to generate the heating power and is defined as fraction of generated heat over electricity consumed.

Formula for calculation

$$COP_{tot} = \frac{Q_{heat,tot}}{E_{el,tot}}$$

$E_{el,tot}$: Overall electrical consumption of MiniStor during heating season.

$Q_{heat,tot}$: Overall provided heating energy of MiniStor during heating season.

Goal: COP > 1.8

Results

$$E_{el,tot} = 1.8 \text{ kW}$$

$$Q_{heat,tot} = 3.25 \text{ kW}_{th}$$

$$COP_{tot} = \frac{3.25 \text{ kW}_{th}}{1.8 \text{ kW}} = 1.81$$

ÉMI determined the above values during their performance measurements (cf. next paragraph for details).

Discussion

The overall COP of 1.81 slightly exceeds the defined target of 1.8 and thus fulfils the requirement of this KPI. The result is based on laboratory measurements conducted by ÉMI and follows the methodology described in Deliverable D6.2, where all input data and calculation steps are documented in detail.

The system was tested under representative winter conditions, with solar input temperatures above 60 °C. Internal energy flows within the MiniStor modules were not included in the calculation. Nonetheless, the measured COP confirms that the system can meet the performance expectations under controlled conditions.

KPI_13 Relative change in thermal energy net consumption

KPI description

Relative change of thermal energy consumption with respect to the heat/cooling energy consumption to satisfy the heat/cooling demand of the building normalised with respect to different climatic conditions (weather influence) and usage influence (change of the number of inhabitants). The energy consumption is calculated over 6 months or the longest possible comparable period in which the MiniStor system is running respectively not running.

Formula for calculation

$$KPI = \frac{(Q_{before} - Q_{after})}{Q_{after}} \cdot 100 \%$$

Q_{before} energy consumption of building's heating/cooling system before MiniStor is installed/operational.

Q_{after} energy consumption of the heating/cooling system when MiniStor is operated (during a comparable period Q_{before}).

Goal: $\geq 40 \%$

Results

KPI_13 quantifies the relative change in thermal energy consumption due to the operation of the MiniStor system. To ensure robustness and comparability, the evaluation is based on a period-wise calculation rather than a global aggregation. For each active MiniStor period (≥ 1 day duration), a corresponding reference period prior to installation was identified based on the same criteria as for KPI_11: equal duration (± 10 min), similar outdoor temperature (± 0.2 °C), and a time offset of one year with a grace period of ± 30 days, during which the system was not installed. For each matched pair of periods, the relative change in thermal energy consumption was calculated according to the formula.

The final site-level KPI is computed as the arithmetic mean of all valid period-wise results:

$$KPI_{13,site} = \frac{1}{N} \sum_{i=1}^N KPI_i$$

With KPI_i the relative change in the period i . This approach ensures that each period contributes equally to the final KPI, avoiding bias from period length or seasonal variability.

Table 3: Relative thermal energy savings (KPI_13) across demonstration sites. All values are given as percentual reductions in thermal energy consumption relative to the respective MiniStor-active periods.

Demo Site	Count: Active periods	Count: $\geq 40 \%$	KPI _{13,site}	Simulated data
Cork	–	–	–	302 %
Kimmeria	–	–	–	155 %
Santiago de Compostela	18	18	307 %	266 %
Sopron	28 – 13 = 15	7	249 %	315 %
Thessaloniki (pre-pilot)	18	8	125.5 %	–

A reduction higher than 100 % is possible as the energy/heat consumption after the installation of the MiniStor system is considered as a reference.

Discussion

The analysis of KPI_13 includes the same set of demonstration sites as KPI_11, namely Sopron, Thessaloniki, and Santiago de Compostela (USC). For these three sites, suitable measurement data were available and allowed for a period-wise evaluation of relative thermal energy savings. Data from Cork and Kimmeria could not be evaluated based on direct measurements due to technical issues during the monitoring phase—a compressor malfunction in Cork and a thermal energy meter failure in Kimmeria. However, simulated data were used for both sites to provide indicative values of expected performance under simulation conditions. In Thessaloniki, no conclusive simulation results could be obtained, and only measured data were considered.

An overview of the measured and simulated KPI_13 results is presented in Table 2. The table includes the number of valid operation periods per site, the number of periods in which the defined KPI target of $\geq 40\%$ was met, and the average site-level result. The simulated values offer a meaningful comparison, highlighting the consistency between modelled and observed system behaviour, and confirming the system's theoretical potential.

All three sites with measured data demonstrate substantial relative reductions in thermal energy consumption, with average KPI values far exceeding the defined target. The highest average reduction was observed at the Santiago de Compostela site (307%), followed by Sopron (249%) and Thessaloniki (125.5%). These high percentages reflect the structure of the KPI formula, which amplifies the relative savings particularly in periods where the net energy consumption during MiniStor operation was low.

As already noted in the discussion of KPI_11, the lower relative savings observed in Thessaloniki can be explained by elevated outdoor temperatures during most of the monitoring periods, which led to limited heating demand. Consequently, both the absolute and relative energy savings were moderate, as the system had only limited opportunity to actively displace thermal energy consumption during periods with moderate to high ambient temperature.

In Sopron, the situation is reversed: while the absolute savings reported under KPI_11 were relatively modest (0.71 kWh/day on average), the relative change reported here is substantial which is explained by the overall low thermal energy demand at the site. Many periods showed little or no heating or cooling activity, inherently limiting the potential for absolute savings. However, the relative savings observed under KPI_13 remained substantial, indicating that MiniStor effectively contributed whenever there was a thermal demand. This consistency between absolute and relative performance strengthens the conclusion that the system performs well, even in low-demand environments.

In Santiago de Compostela, both absolute and relative savings were consistently high, supported by stable system operation and significant thermal loads throughout the measurement periods. This site thus demonstrates the system's full potential under realistic demand conditions.

In conclusion, the results confirm the effectiveness of the MiniStor system in reducing thermal energy consumption across a wide range of boundary conditions. The close alignment between absolute (KPI_11) and relative (KPI_13) indicators supports the robustness of the findings. The inclusion of simulation-based results from Cork and Kimmeria further supports the transferability of the results and suggests that comparable savings can be expected in future deployments, if system operation is stable and thermal demand is present.

KPI_14 Energy losses

This KPI was initially defined to quantify the energy losses within the MiniStor system by comparing the total energy supplied to the system with the actual energy consumed for electricity, heating, and cooling at the building level.

Following the revision of the KPI definition in Deliverable 6.1 in August 2025, KPI_14 was removed from the evaluation scope. Due to the heterogeneous technical configurations across the demonstration sites—including varying heating technologies, grid interfaces, and solar harvesting capacities—it was not feasible to define a harmonised indicator for system-wide energy losses. As a result, no target value was established, and this KPI is no longer part of the final assessment.



KPI_15 RES on-site average use

KPI description

The KPI is the fraction of the time the renewable energy systems (RES) is used, based on the heating and cooling demand. The final value highly depends on building characteristics and available space for RES generation.

Formula for calculation

$$KPI = \frac{T_{RES}}{T_{RES} + T_{NES}} \cdot 100 \%$$

T_{RES} time of activity of the renewable energy system.

T_{NES} time of activity of non-renewable energy system.

Goal: 50 %

Results

The calculation of KPI 15 is based exclusively on periods for which data from the MiniStor system, including production data from the PVT and/or FPC components, are available. All data are resampled to 15-minute intervals to allow for a consistent comparison across production and consumption signals.

For each time step, a binary signal is generated to indicate whether there was renewable energy production (RES): 1 if PVT or FPC output is greater than zero, 0 otherwise.

Simultaneously, a second binary signal is created to reflect whether thermal energy was consumed in the building during the same time step (CONSUMPTION): 1 if energy is consumed, 0 otherwise.

Using Boolean operations, each time step is categorised as follows:

- RES and CONSUMPTION are both true → counted as T_RES
- RES is true and CONSUMPTION is false → also counted as T_RES
- CONSUMPTION is true and RES is false → counted as T_NES
- RES and CONSUMPTION are both false → counted as T_IDLE

Finally, the KPI is calculated as:

$$KPI = \frac{T_{RES}}{T_{RES} + T_{NES}} \cdot 100 \%$$

This approach captures the extent to which renewable energy is available during periods of demand or potential storage, while ignoring periods with incomplete or missing data.

Table 4: RES availability during MiniStor active periods. Time shares of renewable (T_{RES}), non-renewable (T_{NES}), and idle periods (T_{IDLE}) per demonstration site, and resulting KPI 15 values.

Demo Site	T_RES	T_NES	KPI ₁₅	T_IDLE
Santiago de Compostela	57 h	162.25 h	26 %	1156.5 h
Sopron	167.5 h	37.75 h	81.61 %	1599.75 h
Thessaloniki (pre-pilot)	1570.5 h	405 h	79.5 %	548.5 h

Discussion

The results of KPI 15 provide insight into the extent to which the MiniStor system could rely on renewable energy sources (RES) during periods of thermal demand.

The most representative result is observed in Thessaloniki, where a KPI value of 79.5 % was achieved across a substantial dataset with relatively low idle time. This high value indicates that the RES components (PVT and/or FPC) were active during the majority of time steps in which thermal energy was demanded. Despite the known limitations in the orientation and sizing of the solar field at this site, the RES systems still contributed significantly to the overall energy provision, underlining the system's potential for effective integration.

In Sopron and Santiago de Compostela, the KPI values are 81.6 % and 26 %, respectively. However, these results must be interpreted with a grain of salt. In both cases, the idle time—i.e., periods without any RES production and consumption—is disproportionately high, which means that the total number of time steps considered in the analysis ($T_{RES} + T_{NES}$) is relatively low. As a result, the KPI is very sensitive to outliers and short-term fluctuations, making the results less stable and less representative of overall system performance.

Kimmeria is not included in this analysis because MiniStor was not connected to a dedicated RES installation. Instead, it formed part of a larger campus infrastructure including a central solar field.

The demonstration site at Cork could not be evaluated due to missing valid MiniStor data during the analysis period.

In conclusion, the results from Thessaloniki offer the clearest indication of RES integration performance in real-world conditions, while the outcomes from Sopron and Santiago should be considered indicative but not conclusive due to limited active periods.

KPI_16 Visualisation of retrofit design options

KPI description

This KPI assess the feedback of end-users, and suppliers to the new visualization to the new design and retrofitting options.

Formula for calculation

Goal: measured in Likert Scale¹= "Strongly Agree" (4.5/5), easy and fast access.

Discussion

KPI 16 was intended to assess the effectiveness of visualisation tools developed to support the design and retrofitting process of the MiniStor system. The original approach foresaw collecting qualitative feedback from relevant stakeholders (e.g., end-users, planners, and suppliers) using structured Likert-scale evaluations.

However, in practice, the application and systematic evaluation of these visualisation tools were not implemented to a degree that would allow for a meaningful assessment. This is primarily due to the focus of the demonstration phase being placed on technical integration and system operation, rather than on participatory planning or design processes involving the end-users.

Furthermore, since the retrofitting scope and boundary conditions varied considerably across the demonstration sites, a consistent and comparable evaluation of visualisation tools could not be established. As a result, KPI 16 cannot be quantified, and no conclusion can be drawn regarding the usability or added value of the tools within the scope of this project.

¹ Cf. (Likert, 1932)

KPI_17 Electrical energy savings

KPI description

The relative change in electrical consumption between the situations with and without MiniStor system relative to the final electrical energy consumption. The energy consumption is calculated over 6 months or the longest possible comparable period in which the MiniStor system is running respectively not running.

Formula for calculation

$$KPI = \frac{(E_{after} - E_{before})}{E_{after}} \cdot 100 \%$$

E_{before} electrical energy consumption from the grid while MiniStor is not running.

E_{after} electrical energy consumption from the grid while MiniStor is running (over a period comparable to E_{before}).

Goal: < 0 %

(the overall aim is to reduce the grid's electricity consumption while reducing the green house gas emissions)

Results

KPI_17 quantifies the relative change in electrical energy consumption due to the operation of the MiniStor system. To ensure robustness and comparability, the evaluation is based on a period-wise calculation rather than a global aggregation. For each active MiniStor period (≥ 1 day duration), a corresponding reference period before installation was identified based on the same criteria as KPI_11 (and KPI_18): equal duration of period (± 10 min), similar outdoor temperature (± 0.2 °C), and a time offset of one year with a grace period of ± 30 days, during which the system was not installed and the MiniStor system was installed and not in maintenance. For each pair of matched periods, the relative change in electrical energy consumption was calculated according to the formula.

The final site-level KPI is computed as the arithmetic mean of all valid period-wise results:

$$KPI_{17,site} = \frac{1}{N} \sum_{i=1}^N KPI_i$$

With KPI_i the calculated KPI value for the considered period i . This approach ensures that each period contributes equally to the final KPI, avoiding bias from period length or seasonal variability.

Table 5: Relative electrical energy savings (KPI_17) across demonstration sites. All values are given as percentage change in electrical energy consumption relative to the respective MiniStor-active periods.

Demo Site	Count: Active periods	Count: <= 0 %	KPI _{17,site}	Simulated data
Cork	–	–	–	+ 11.1 %
Kimmeria	35 – 24 = 11	7	- 505 %	-3.7 %
Santiago de Compostela	18	8	- 1 %	+ 1.6 %
Sopron	28 – 2 = 26	10	+ 0.3 %	+ 6.3 %
Thessaloniki (pre-pilot)	18	10	- 6 %	–

Discussion

The analysis of KPI_17 follows the same methodological approach as KPI_11 and KPI_18, focusing here on the relative change in grid electricity consumption before and after the installation of the MiniStor system. The results are based on the comparison of matched periods and are summarised in Table 5, including both measured and simulated values.

For most sites, the number of valid comparison periods is relatively small, which limits the significance of the findings. In Kimmeria, only 11 of 35 periods could be used, as 24 periods showed no electrical consumption before installation which could be linked to absence of the students. In Sopron and Santiago de Compostela, overall consumption levels were low, and the observed variations are correspondingly small. These limitations mean that the results should be interpreted with great caution.

Measured data from Thessaloniki indicate a moderate reduction in electricity consumption (-6%), suggesting a potential contribution of the MiniStor system to reduced grid dependence. In Sopron and USC, relative changes were close to zero, while the extreme value observed in Kimmeria (-505%) is likely an artefact of very low denominators in some periods and should not be interpreted as representative.

Simulated data provide additional reference points but show no consistent trend across sites. Slight increases are observed for Cork, Sopron, and USC, while a minor decrease is reported for Kimmeria.

Overall, while some measured data suggest a reduction in grid electricity consumption due to MiniStor, the sample sizes are too limited to draw firm conclusions. In addition, site-specific factors such as user behaviour, daily usage patterns, and household occupancy have a significant influence on electricity demand and system interaction. These factors vary both across sites and over time, further complicating the interpretation of relative changes in electrical energy use. A more reliable assessment would require extended, uninterrupted monitoring over complete seasonal cycles and with consistent usage profiles.

KPI_18 Change in electrical consumption from grid

KPI description

This KPI measures how much the electrical energy is taken from the grid. This KPI will serve to compare by how much the energy import from the grid could be reduced by the installation of the MiniStor system.

Formula for calculation

$$KPI = E_{after} - E_{before}$$

E_{before} electrical energy consumption from the grid while MiniStor is not running.

E_{after} electrical energy consumption from the grid while MiniStor is running (over a period comparable to the one used to calculate E_{before}).

Results

The scatter plots compare electrical energy consumption before and after the installation of the MiniStor system. Each data point represents one monitoring period. The x-axis shows the energy demand during the reference period (before the installation of the MiniStor), while the y-axis shows the energy consumption during operation of the MiniStor system. The size of each point indicates the duration of the period in days, and the colour reflects the average outdoor temperature during the respective interval. The dashed line ($y = x$) indicates equal consumption before and after the installation; values below the line represent thermal energy savings.

The assessment of KPI_18 is based on a period-wise comparison of electrical energy consumption before and after the installation of the MiniStor system. In a first step, all time intervals during which MiniStor was actively operating for at least 1 day were identified. For each of these active periods, a corresponding reference period from the previous year was selected, following these strict matching criteria:

- The reference period must have the same duration (± 10 min) as the active MiniStor period,
- The average outdoor temperature must fall within a tolerance range of ± 0.2 °C,
- The reference period must be located approximately one year earlier, with a maximum deviation of ± 30 calendar days, and
- The MiniStor system must not have been installed or operational during the reference period.

This matching procedure ensures a high degree of comparability between pre- and post-installation conditions, allowing the observed differences in energy consumption to be attributed primarily to the operation of the MiniStor system.

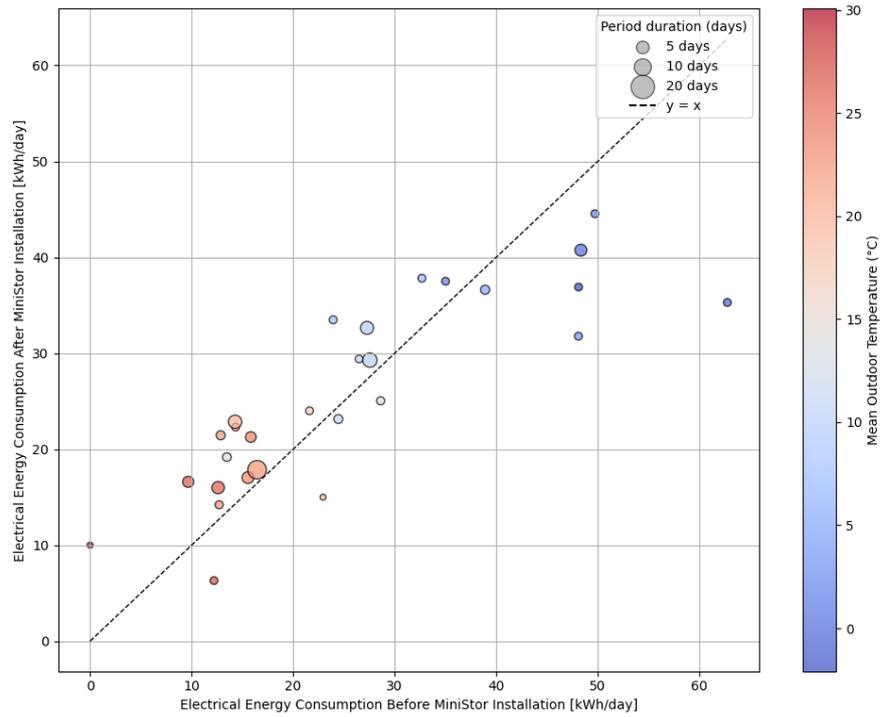


Figure 5: Sopron – Comparison of electrical energy consumption before and after MiniStor installation. Number of active periods: 28 (of which 2 showed no electrical energy consumption and were excluded from the calculation). Average change in electrical energy consumption: 0.004 kWh/day.

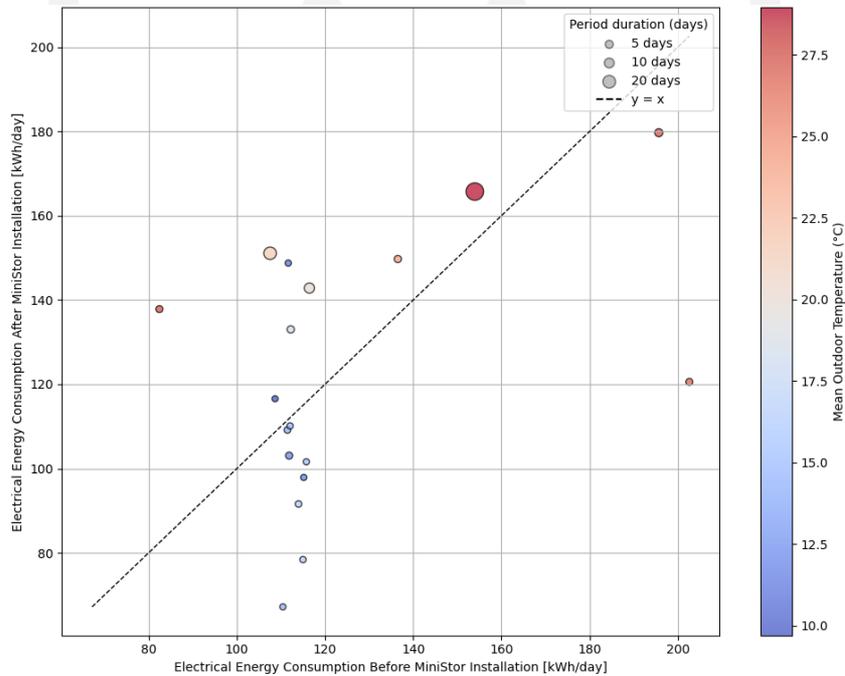


Figure 6: Thessaloniki – Comparison of electrical energy consumption before and after MiniStor installation. Number of active periods: 18. Average saving in electrical energy consumption: 1.6 kWh/day.

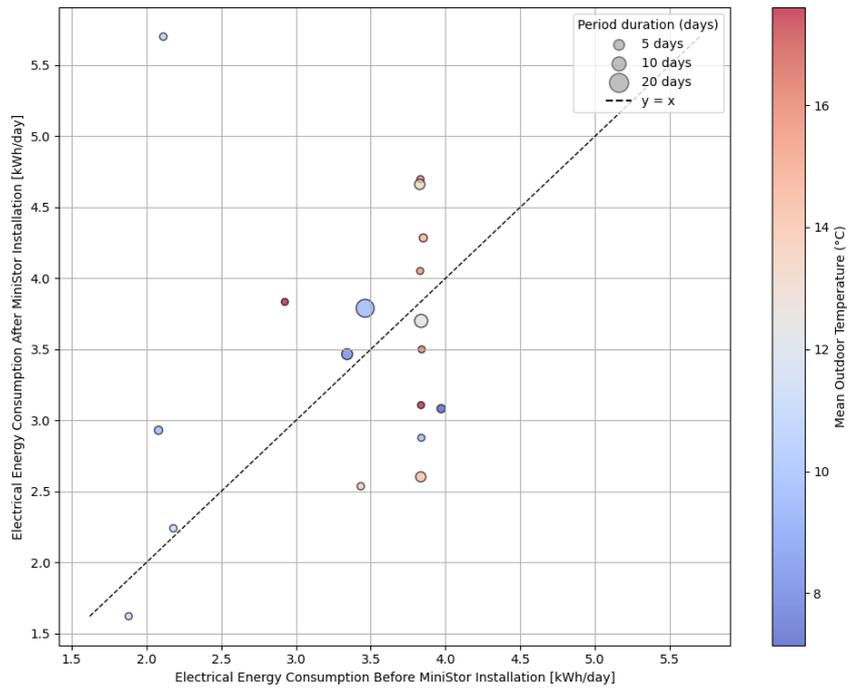


Figure 7: Santiago de Compostela – Comparison of electrical energy consumption before and after MiniStor installation. Number of active periods: 18. Average change in electrical energy consumption: 0.15 kWh/day.

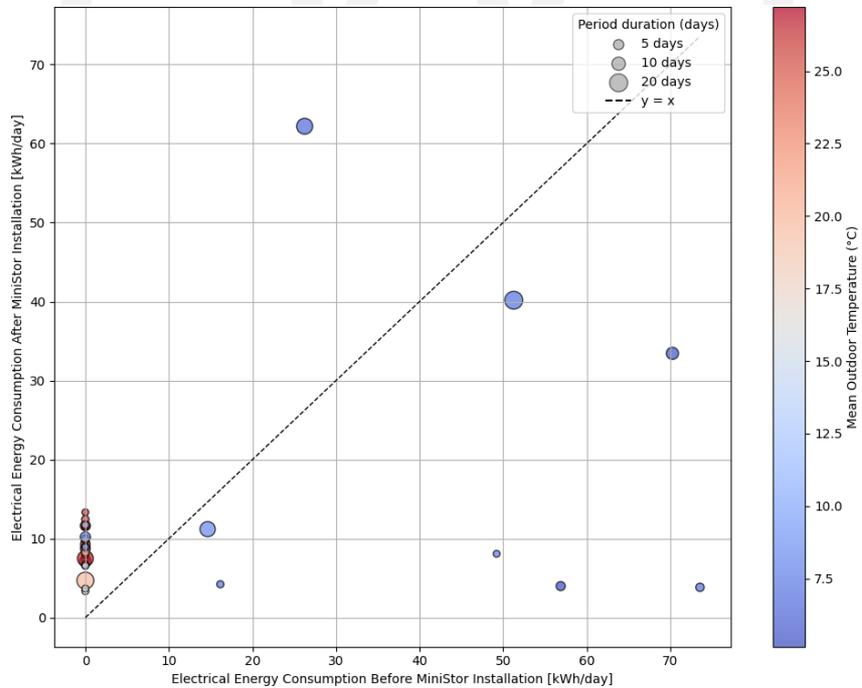


Figure 8: Kimmeria – Comparison of electrical energy consumption before and after MiniStor installation. Number of active periods: 35 (of which 24 showed no electrical energy consumption before installation and were excluded from the calculation). Average saving in electrical energy consumption: 0.76 kWh/day.

Table 6: Overview of absolute electrical energy savings (KPI_18) at all demonstration sites. The table summarises the number of evaluated periods and the resulting average absolute electrical energy change in kilowatt-hours per day.

Demo Site	Count: Active periods	Mean absolute energy change (measured)	Mean absolute energy change (simulated)
Cork	–	–	+ 2.07 kWh/day
Kimmeria	35 (-24)	+ 0.76 kWh/day	- 2.2 kWh/day
Santiago de Compostela	18	+ 0.15 kWh/day	- 0.83 kWh/day
Sopron	28 (-2)	+ 0.004 kWh/day	+ 0.6 kWh/day
Thessaloniki (pre-pilot)	18	- 1.6 kWh/day	–

Discussion

The analysis of KPI_18 includes data from four demonstration sites, based on either measured or simulated values. The KPI evaluates the change in electrical energy consumption from the grid before and after the installation of the MiniStor system. For Sopron, Thessaloniki, Santiago de Compostela (USC), and Kimmeria, period-wise comparisons were carried out using matched monitoring intervals, following the same methodology as applied for KPI_11, KPI_13 and KPI_17. For the Cork site, no measured data were available due to technical issues during the monitoring phase, but simulation-based results are included to estimate the expected impact.

Table 6 summarises the number of valid active periods and the resulting average change in electrical energy consumption per day. Positive values indicate a net increase in grid electricity usage following MiniStor installation, while negative values represent a reduction. Among the sites with measured data, Thessaloniki shows the clearest benefit, with an average reduction of 1.6 kWh/day in electrical grid consumption.

In contrast, the measured values for Sopron and Santiago de Compostela show marginal increases in daily grid consumption (+0.004 kWh/day and +0.15 kWh/day, respectively). These minor changes fall within the expected variation for residential-scale systems and are not necessarily indicative of a negative performance trend. In Sopron, very low baseline consumption during the active periods constrained the potential for measurable reduction, while in USC, operational characteristics may have favoured internal system loads or temporary inefficiencies.

In Kimmeria, the average measured change was slightly positive (+0.76 kWh/day), although the result is based on only 11 valid comparison periods out of 35 due to the exclusion of 24 periods with zero pre-installation electrical consumption. This limitation reduces the robustness of the site-level result. Furthermore, it should be noted that the absence of pre-installation consumption data in nearly 70 % of the periods introduces a potential bias toward unfavourable interpretations. As a result, the measured increase in grid usage at this site should be treated with caution. Interestingly, the corresponding simulation for Kimmeria indicates a net reduction of 2.2 kWh/day, suggesting that the observed increase may reflect temporary system conditions or measurement constraints rather than systematic underperformance.

Overall, the results for KPI_18 indicate that the MiniStor system can contribute to reducing grid-based electricity consumption under certain conditions. However, the magnitude of the impact varies across sites and appears sensitive to local usage patterns, control strategies, and system configuration. Furthermore, the number of valid periods remains limited. Therefore, while the results are promising in selected cases, a broader and more continuous dataset would be required to draw definitive conclusions regarding the system's effect on electrical grid consumption.

KPI_19 Share of renewables

KPI description

Fraction of renewable energy sources used to operate the MiniStor system.

Formula for calculation

$$KPI = \frac{E_{renewables}}{E_{renewables} + E_{grid}} \cdot 100 \%$$

$E_{renewables}$ electrical and thermal demand of the MiniStor system.

E_{grid} electrical energy extracted from the grid by the MiniStor system.

(the aim is to maximise this KPI. As its value depends strongly on the location and the weather conditions, no target is indicated)

Results

KPI 19 is calculated as the share of renewable energy used to operate the MiniStor system relative to the total energy demand of MiniStor. The data used for this KPI are derived from simulation results provided by EMI, which reflect site-specific renewable energy generation potential and system performance.

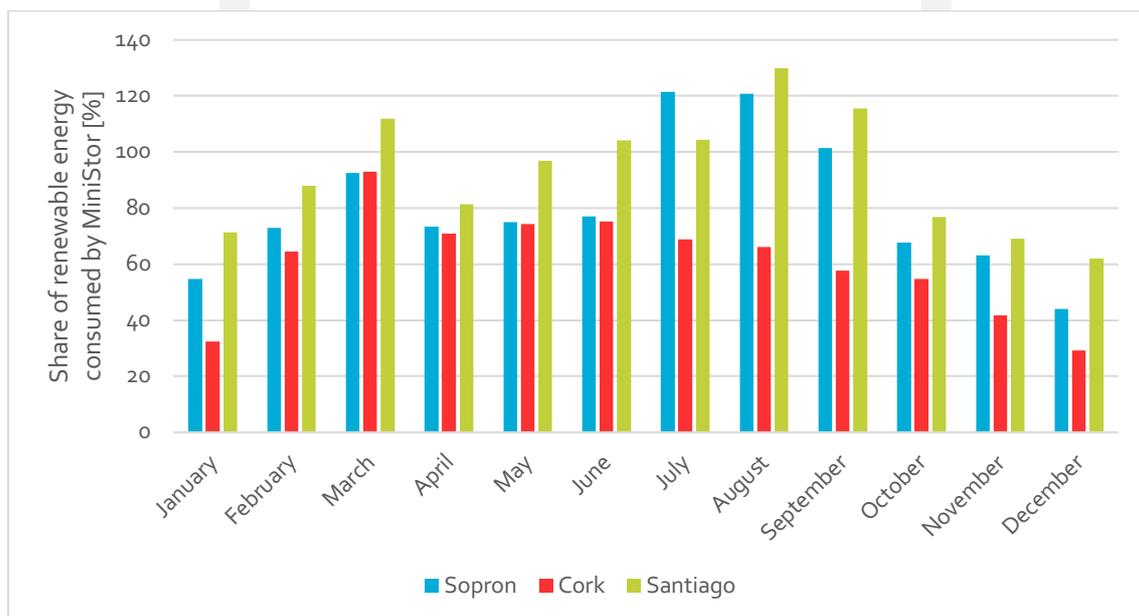


Figure 9: Monthly share of renewable energy sources (RES) consumed by the MiniStor system at the demonstration sites in Sopron, Cork, and Santiago de Compostela, based on simulation results from EMI. Values above 100% indicate that more RES energy was produced, than consumed by the MiniStor system.

Values above 100% indicate that more renewable energy was produced than consumed by the MiniStor system. The surplus energy (e.g. electricity) can be directly fed into the grid or stored in batteries.

Table 7: Average share of renewable energy sources (RES) used to operate the MiniStor system at selected demonstration sites, based on simulation data from EMI.

Demo Site	Average RES share [%]
Cork	61
Santiago de Compostela	91
Sopron	80

Kimmeria is excluded from this KPI, as MiniStor uses the pre-existing RES infrastructure (solar thermal + biomass boiler), and there is no separate or dedicated RES installation attributable to the MiniStor system.

Discussion

This KPI highlights the extent to which MiniStor can be operated using renewable energy sources at different demonstration sites. The results show strong variability between locations, reflecting differences in local climate, solar irradiance, system design, and installation configuration.

- Santiago achieved the highest share of RES (91%), benefiting from favourable solar conditions and an optimised integration of thermal and electrical renewable inputs.
- Sopron reached a solid 80% share of renewables, demonstrating good renewable coverage throughout most of the year, especially in summer months.
- Cork performed more modestly with a 61% average, likely due to less favourable weather conditions and lower solar yields.

It is important to note that the share of renewables varies seasonally, with highest values observed in summer months, as illustrated in the Figure above. This dominance reflects the typical availability profile of solar-based systems.

Due to the prototype nature of MiniStor (TRL 7) and the limited duration of operation under fully representative conditions, these values are based on simulation outputs rather than measured data. Nevertheless, they offer valuable insights into the potential of the system and indicate a strong alignment with the project goal of maximising renewable energy usage in decentralised energy storage and supply systems.

KPI_20 Self-electricity production / self-sufficiency ratio

KPI description

Percentage of consumed electrical energy that is produced by the PVT panels.

Formula for calculation

$$KPI = \frac{E_{renewables}}{E_{renewables} + E_{grid}} \cdot 100 \%$$

$E_{renewables}$

electrical production of the PVTs.

E_{grid}

electrical energy extracted from the grid not consumed by the MiniStor system.

(the aim is to maximise this KPI. As its value depends strongly on the location and the weather conditions, no target is indicated)

Results

KPI 20 quantifies the share of electrical energy that is covered by on-site renewable production from the PVT system. It is calculated as the proportion of total daily electrical consumption in the building that was produced by the MiniStor PVT system.

Daily values were averaged across all monitoring periods in which sufficient data was available.

- **Thessaloniki:** 56 days analysed, average self-sufficiency ratio: 2.4 %
- **Santiago de Compostela:** 20 days analysed, average self-sufficiency ratio: 85.9 %
- **Kimmeria:** not evaluated due to lack of data on grid consumption and absence of MiniStor specific PVT installation.
- **Sopron:** No data available for PVT production.

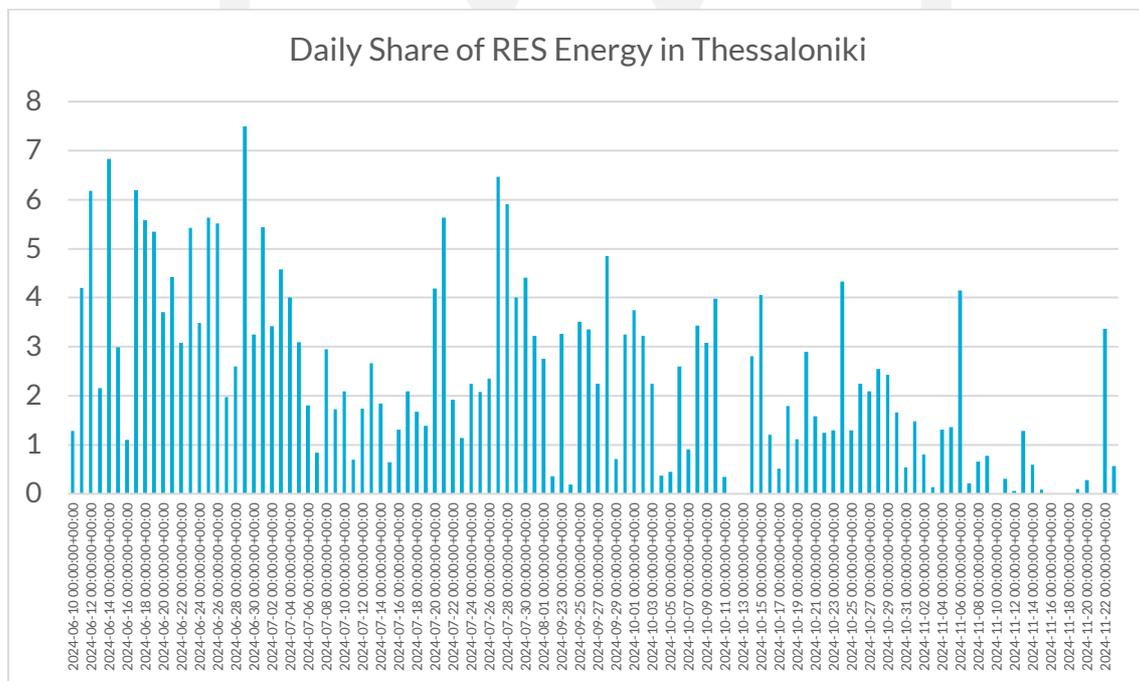


Figure 10: Daily share of PVT-produced and grid-supplied electricity at the Thessaloniki site. The average self-sufficiency ratio over the monitored period was 2.4%. The MiniStor system covered only a very small fraction of the building's electrical demand from on-site renewable sources, due to suboptimal PVT array positioning and high electricity consumption.

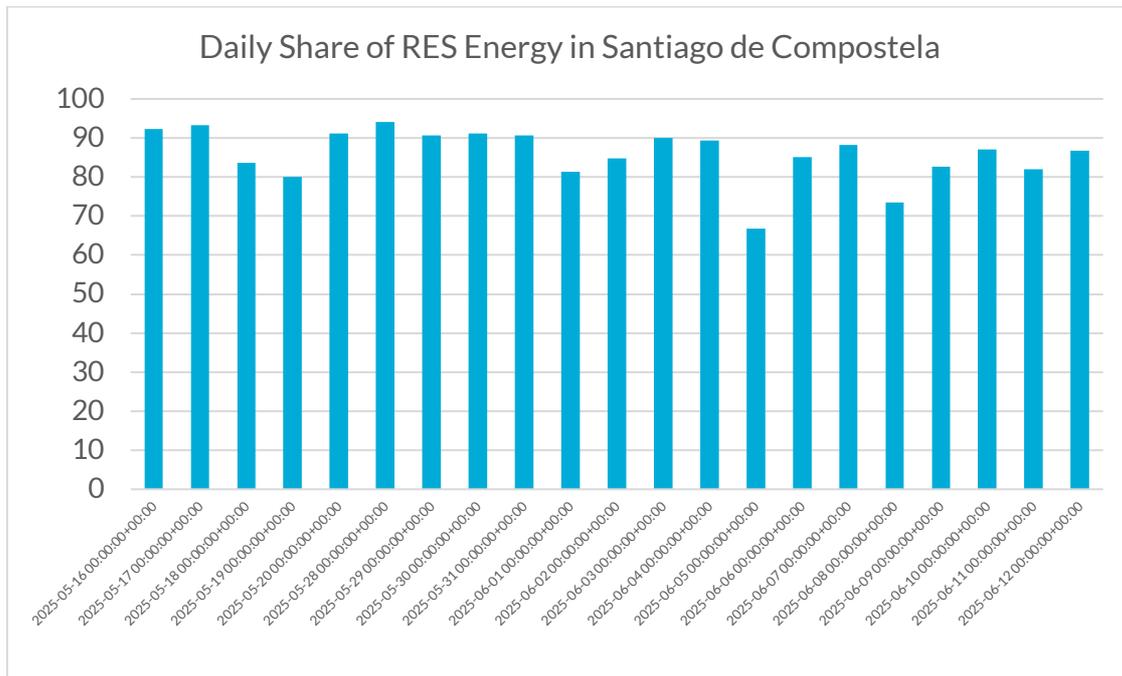


Figure 11: Daily share of PVT-produced and grid-supplied electricity at the Santiago de Compostela site. The average self-sufficiency ratio over the monitored period was 85.9 %. The MiniStor system covered the majority of its electricity demand through local PVT generation, indicating an efficient system design and favourable climatic conditions.

Discussion

KPI 20 reflects the degree to which on-site renewable electricity production contributes to the building's overall electrical demand. High values indicate that a significant portion of the building's electricity consumption is covered by the MiniStor PVT system, reducing dependence on grid-supplied energy.

At the Santiago de Compostela site, the self-sufficiency ratio averaged 85.9 %, demonstrating a strong alignment between solar production and on-site demand. This suggests both high system efficiency and favourable solar conditions during the evaluation period.

In contrast, the Thessaloniki site shows a considerably lower self-sufficiency ratio of 2.4 %. This outcome is primarily due to two factors: first, the building in Thessaloniki exhibits a relatively high overall electricity demand; second, the orientation and tilt of the PVT array are suboptimal for the local solar conditions, significantly limiting the renewable yield. As a result, the contribution of the PVT system to the site's electrical needs remained marginal during the monitoring period.

For Sopron, no data on PVT electricity production were available at the time of reporting. As a result, the KPI could not be calculated for this site.

At the Kimmeria site, the MiniStor system was not equipped with a dedicated PVT installation. Therefore, the KPI is not applicable in this context.

These findings underscore the importance of appropriate system dimensioning, demand profiling, and site-specific optimisation (especially regarding PVT placement) in achieving meaningful gains in electrical self-sufficiency through renewable integration.

KPI_21 Maximum hourly energy surplus / deficit (kWh)

KPI description

Maximum hourly surplus or deficit of energy stored by the MiniStor system compared to demand in the respective moment.

Formula for calculation

$$KPI = E_{MiniStor} - E_{demand}$$

E_{demand} electrical and thermal demand of the building at the considered moment.

$E_{MiniStor}$ energy stored/produced by MiniStor.

Revision August 2025:

The monitoring system was not designed to provide sufficiently detailed data on the amount of energy supplied by the MiniStor system and thus cannot capture the balance between surplus and deficit. As a consequence, this KPI cannot be calculated, and no target value is defined.

Discussion

The calculation of KPI 21—defined as the maximum hourly surplus or deficit between the energy provided by MiniStor and the building's corresponding demand—was not possible due to missing measurement data. Specifically, no reliable data exist on the thermal output of the MiniStor system with hourly resolution.

While the building's demand and grid-based energy consumption were recorded, the key variable required for this KPI—the actual thermal energy delivered by MiniStor on an hourly basis—was not measured directly at any of the demonstration sites. The available simulation data cannot be used as a substitute, as they are not available at sufficient temporal resolution.

Without direct measurement of thermal output at high frequency, the comparison to instantaneous demand—as required by the KPI definition—cannot be made.

KPI_22 Expected lifetime

KPI description

The expected lifetime of the system based on estimations of the individual components.

Formula for calculation

Component manufacturers' details on life expectancy.

Goal: > 20 years
(typical lifetime expectation for HVAC systems)

Results

According to the Life Cycle Costing and Environmental Assessment reported in D7.3, the expected lifetime of key components is as follows:

- TCM module: 20 years
- PCM modules: 20 years
- Heat pump: 15–20 years
- PVT collector: 25 years
- Other auxiliaries: 10–15 years (considered to be part of the maintenance kits)

The integrated system is thus designed for a functional lifespan exceeding 20 years under standard operating conditions.

Discussion

The expected lifetime of the MiniStor system meets the defined KPI target. All critical components have a projected service life of 15 to 25 years, with the majority rated above 20 years. These values are based on manufacturer data, technical documentation, and prior project experience, as documented in D7.3.

Auxiliary components such as pumps and valves—typically associated with shorter lifespans (10–15 years)— can be easily replaced during routine maintenance without affecting the overall system operation or safety integrity.

Assuming proper installation and regular maintenance, the functional lifespan of the integrated system is expected to exceed 20 years. The KPI is therefore considered fulfilled.

KPI_23 System reliability

KPI description

This KPI quantifies the system's reliability by calculating the share of the time the system is performing its intended tasks compared to the time the system is operated.

Formula for calculation

$$KPI = \frac{T_{operational}}{T_{installed}}$$

$T_{operational}$ time the MiniStor system was operational (storing or ready to store energy).

$T_{installed}$ time the MiniStor system was installed.

Results

Data to calculate the reliability KPI for each demo site was gathered semi-manually from direct reports by the partners responsible for manufacturing and commissioning, as well as by the on-site teams. Since the original MiniStor monitoring system did not track continuous "operationality," this KPI was derived from partner logs and commissioning records. Going forward, the upgraded SCADA monitoring infrastructure will automatically capture this metric; however, occasional post-processing will still be required to flag sensor recalibrations.

Below is the dataset for each demo site and the resulting KPI at the time of preparation:

Table 8: Operational time of the MiniStor System per demo site compared to time since installation, including resulting KPI for availability.

Demo Site	Installation date	Time installed	Operational time	KPI
Cork	02/04/2025	75 days	0 days	0%
Kimmeria	29/05/2024	383 days	250 days	65%
Santiago de Compostela	25/09/2024	264 days	70 days	27%
Sopron	05/02/2025	131 days	38 days	29%
Thessaloniki (pre-pilot)	07/03/2024	466 days	153 days	33%

Discussion

Although the MiniStor prototypes are fully commissioned at all five sites, the observed reliability remains below 70 % in all locations. Several factors contributed:

- **Sensor calibration:** Early field tests revealed drift in ammonia levels, causing shutdowns when readings fell outside predefined thresholds. Commissioning the sensor network took several iterations for calibration.
- **Ammonia compressor malfunctions:** the TCM loop's ammonia (NH₃) compressor experienced repeated failures, which in turn triggered automatic safety interlocks and suspended both charge and discharge cycles. Furthermore, limited availability of spare parts and extended lead times for distribution and repairs significantly prolonged system downtime before the MiniStor units could be ready for the whole operation.

Due to a defect in the compressor, the MiniStor system in Cork was unable to start regular operation by the time the data was analysed. However, as the system is installed, it is still listed.

Given these early-stage challenges typical of first-generation prototypes, the 65% reliability in Kimmeria demonstrates the potential.

KPI_24 User acceptance

KPI description

The degree of acceptance of MiniStor energy storage system by its users.

Formula for calculation

$$KPI = \frac{\sum_{i=1}^{N_{users,q}} acc_i}{N_{users,q} \cdot 10}$$

acc_i answer of the i inhabitant regarding the system acceptance, expressed on a scale of 1 (very low acceptance) to 10 (very high acceptance).

$N_{users,q}$ number of inhabitants providing feedback.

Goal: exceeding 95 %
(only 1 out of 20 persons rejects the MiniStor system)

Results

$$KPI = \frac{10 + 10 + 10 + 10 + 10 + 10 + 10 + 10 + 10 + 10 + 10 + 10}{12 \cdot 10} = \frac{120}{120} = 1 = 100\%$$

Discussion

User acceptance of the MiniStor system was assessed using a 10-point Likert scale, where respondents indicated their overall satisfaction with and willingness to adopt the technology. The resulting KPI reached the maximum possible value of 1.0 (or 100 %), clearly meeting the defined target of exceeding 95 %.

All 12 respondents provided the highest possible rating (10/10), indicating unanimous approval of the system. While this outcome strongly supports the acceptability of the MiniStor solution among users, the small number of respondents must be taken into account. The initial KPI framework aimed for a broader sample (e.g. 20 users), but the actual number of participating individuals was limited due to the scale and occupancy conditions of the pilot sites.

Despite the limited sample size, the consistently high scores suggest that the system was perceived positively by users in terms of comfort, reliability, and integration into the residential environment.

KPI_25 Thermal comfort reported by users

KPI description

Assessment of the thermal comfort preservation achieved by MiniStor, as reported by its users.

Formula for calculation

$$TC_x = \frac{\sum_{i=1}^{N_{users,q}} TC_{i,x}}{N_{users,q} \cdot 10}$$

$$KPI_{thermal\ comfort} = \frac{TC_{after}}{TC_{before}}$$

$TC_{i,x}$ answer of the i inhabitant regarding the thermal comfort preservation, expressed on a scale of 1 (very low thermal comfort) to 10 (very high thermal comfort) under situation x (before, after).

$N_{users,q}$ number of inhabitants providing feedback.

Goal: above 95 %

(only 1 out of 20 persons notices a difference in the thermal comfort)

Results

$$TC_{before} = \frac{5 + 5 + 5 + 5 + 5 + 8}{6 \cdot 10} = \frac{33}{60} = 0.55$$

$$TC_{after} = \frac{10 + 10 + 10 + 10 + 10 + 10 + 8 + 8 + 8 + 10 + 10 + 10 + 10}{12 \cdot 10} = \frac{114}{120} = 0.95$$

$$KPI_{thermal\ comfort} = \frac{0.95}{0.55} = 1.72 = 172 \%$$

Discussion

The thermal comfort KPI is derived from user-reported satisfaction levels before and after the installation of the MiniStor system, based on a 10-point Likert scale. The calculated KPI value of 1.72 indicates a 72 % relative increase in perceived thermal comfort. This improvement is reflected in the average score rising from 0.55 (before) to 0.95 (after).

Although the target was to collect responses from at least 20 individuals, this number could not be reached. Furthermore, the number of respondents before the installation (6 users) was significantly lower than after the installation (12 users). This discrepancy limits the statistical robustness of the result but nonetheless suggests a clear trend.

The post-installation data indicate consistently high comfort ratings (majority ≥ 8), whereas the baseline values before installation were considerably lower. This change likely reflects the limitations of the previous heating and cooling systems, which were addressed by the MiniStor solution.

Despite the limited sample size, the KPI exceeds its target of >95 % satisfaction and supports the conclusion that the system effectively maintains or improves thermal comfort in real-world residential settings.

KPI_26 Change in perceived thermal comfort

KPI description

Evaluation of the change of the perceived thermal comfort, variability of the indoor room temperature and humidity achieved with the MiniStor system. Due to the limited number of inhabitants only the change in the qualitative feedback will be considered instead of standardised procedures such as Fanger's method².

Formula for calculation

The change in the qualitative feedback from the demo site inhabitants as provided in the questionnaire will be the key input for this KPI (see KPI_25). In case the quality and quantity of the measurements of temperature and humidity is sufficient, the change in the variability will provide a second contribution to this the KPI.

Results

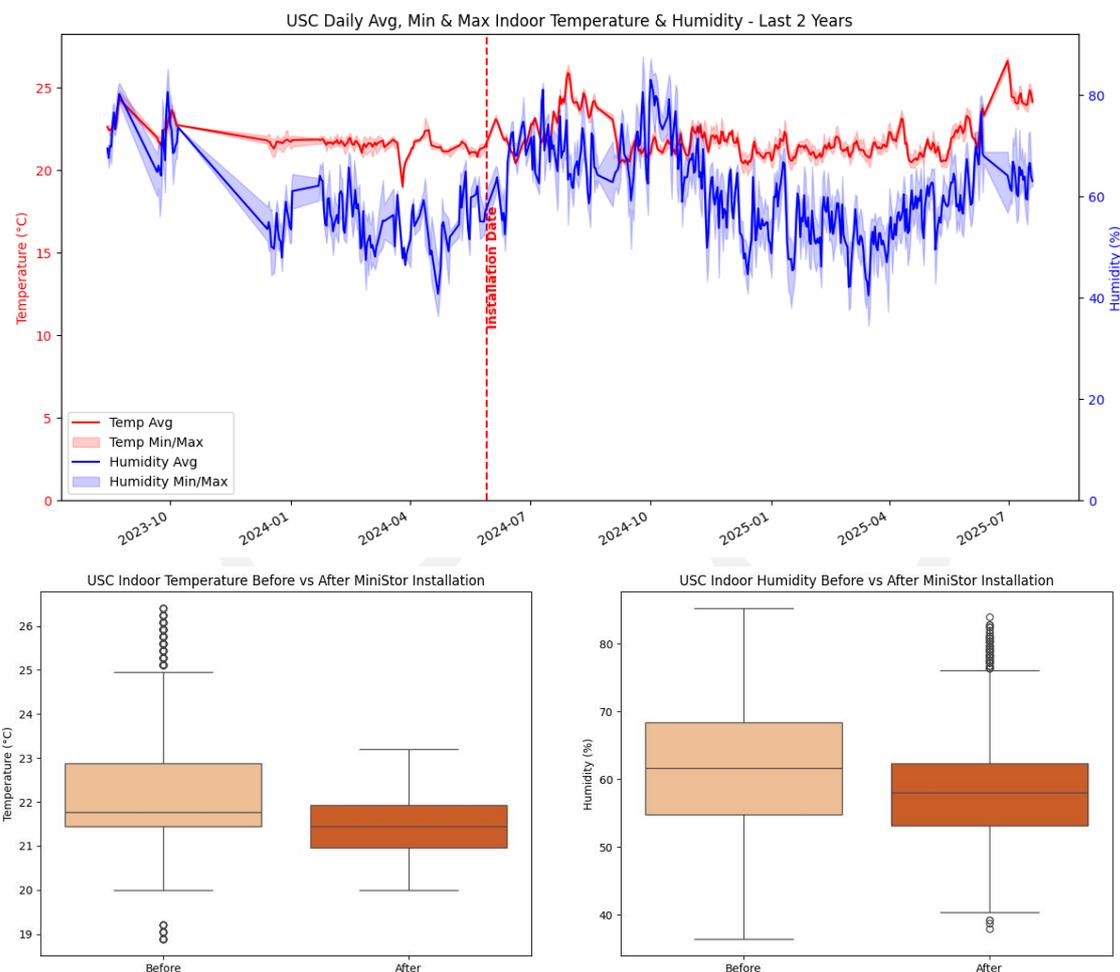


Figure 12: Indoor temperature and humidity at the demonstration site in Santiago de Compostela over a two-year period. The top graph shows daily average, minimum and maximum temperature and relative humidity, with the MiniStor installation marked by a vertical dashed line. The boxplot below compare distributions of temperatures and humidity before and after MiniStor installation.

² Fanger, P Ole (1970). Thermal Comfort: Analysis and applications in environmental engineering. McGraw-Hill.

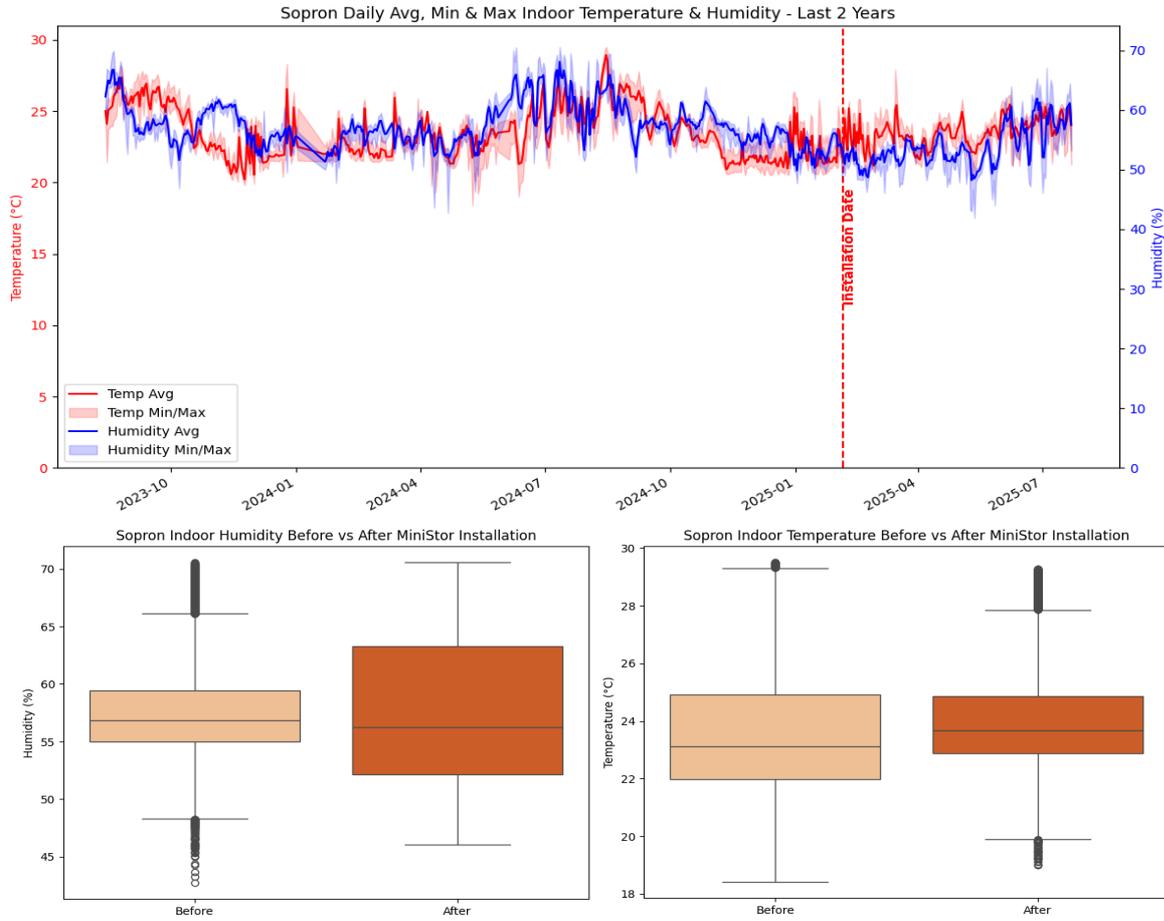


Figure 13: Indoor temperature and humidity at the demonstration site in Sopron over a two-year period. The top graph shows daily average, minimum and maximum temperature and relative humidity, with the MiniStor installation marked by a vertical dashed line. The boxplots below compare distributions of temperature and humidity before and after installation.

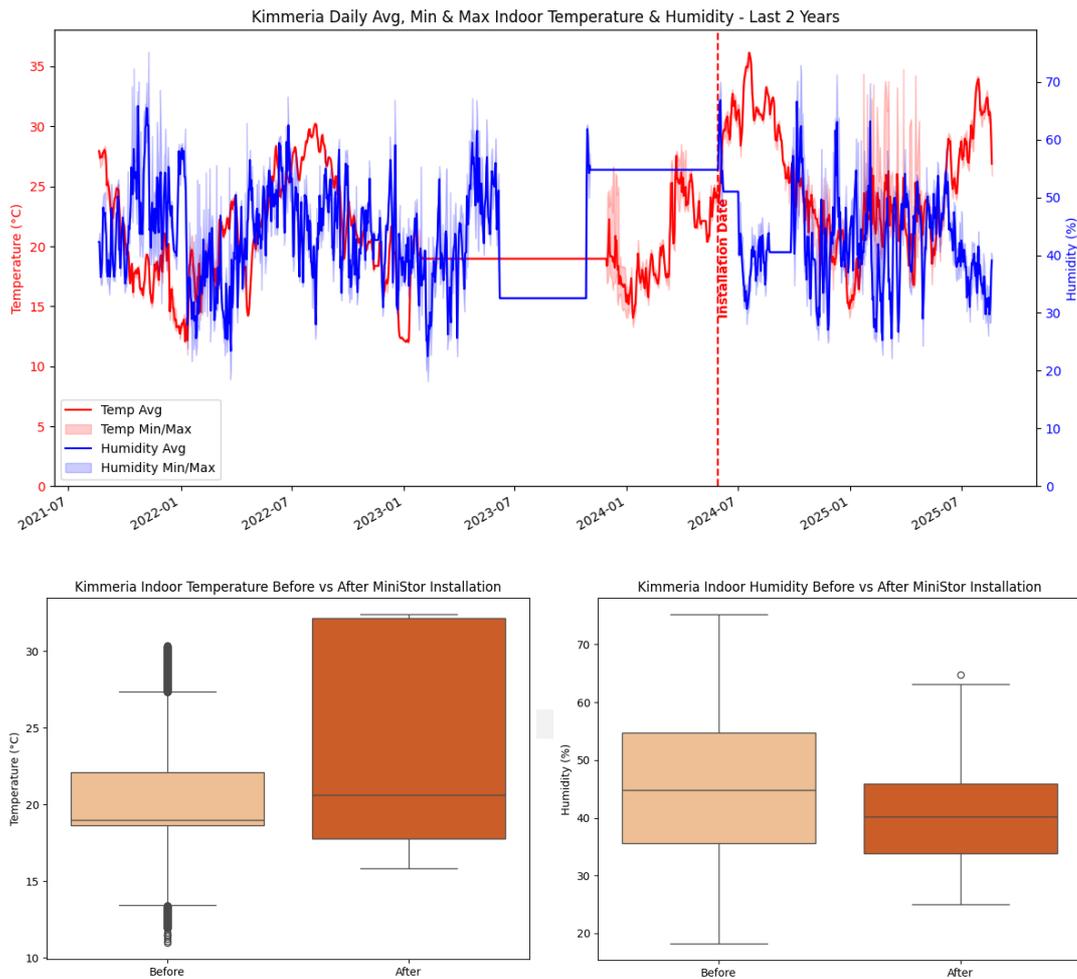


Figure 14: Indoor temperature and humidity at the demonstration site in Kimmeria over a two-year period. The top graph shows daily average, minimum and maximum temperature and relative humidity, with the MiniStor installation marked by a vertical dashed line. The boxplots below compare distributions of temperature and humidity before and after installation.

Discussion

KPI_26 assesses the change in thermal comfort experienced by occupants, based primarily on qualitative feedback (see KPI_25) and, where available, on sensor-based evaluation of temperature and humidity variability before and after MiniStor installation. Feedback from the participating inhabitants indicates that the perceived thermal comfort was not negatively affected by the deployment of the MiniStor system.

In addition, indoor environmental data (temperature and relative humidity) were analysed at three of the five demo sites. As shown in the comparative plots, no increase in temperature or humidity variability was observed after MiniStor installation. In Sopron and USC, temperature fluctuations slightly decreased, and relative humidity remained stable or was reduced. In Kimmeria, post-installation data exhibit greater variability.

Data from Thessaloniki were excluded from the analysis due to missing indoor temperature measurements and the fact that the pre-pilot building was not permanently inhabited. Similarly, Cork was excluded because the MiniStor system was not in active use during the relevant monitoring period.

In conclusion, while the available data do not provide evidence of a substantial improvement in thermal comfort, they do indicate that MiniStor had no negative impact on perceived or measured comfort levels.

KPI_27 Number of users involved in demonstration activities

KPI description

The number of participants that will be involved in demonstration and/or dissemination activities such as homepage visitors, webinars, trade shows, conferences etc.

Formula for calculation

$$KPI = N_d$$

N_d number of participants (input from WP8).

Goal: ≥ 1000 participants.

(at least 20 dissemination events (conferences, webinars, workshops) with on average 50 participants.

Results

Workshops & Conferences:

Stakeholders & mid-term workshop, National workshops: 937

Final Conference: 164

Demonstration & Dissemination workshops: 796

Workshops & Conferences:

$$896 + 164 + 1154 = 2214$$

Digital communication:

Website visitors: 44'915 (unique IPs) from July 2024 to June 2025

Social Media Follower: 486 (Twitter) + 248 (Linkedin) = 734

Youtube views: 1004

Digital communication:

$$44915 + 734 + 1004 = 46'653$$

$$KPI = N_d = 1'897 + 46'653 = 48'550$$

Discussion

The number of participants reached through demonstration and dissemination activities – such as workshops, conferences, and stakeholder events – totals to 2'214, clearly exceeding the KPI 27 target of 1'000 participants. These activities, as reported in Deliverable D8.2, provided a platform for direct exchange, practical demonstrations of the MiniStor system, and constructive dialogue with key stakeholders from industry, policy, and research.

In addition to these on-site engagements, Deliverable D8.2 also documents substantial visibility achieved through digital communication channels. Website visitors, social media followers, and YouTube views together accounted for a further 48'550 recorded interactions, significantly extending the project's outreach and ensuring that MiniStor's objectives and results reached a wide audience beyond the physical events.

While the KPI target was already met through participation in workshops and conferences alone, the additional digital engagement underscores the complementary role of online channels in maximising awareness and dissemination impact.

KPI_28 Compliance: NH₃ usage & storage

KPI description

Pass/Fail criterion whether the MiniStor system complies with the local legal/safety regulations as well as national compulsory regulations. In addition, also the overlap with national standards will be investigated.

Formula for calculation

Compliance with European standard EN 378:2016 for relevant refrigerant requirement.

Results

The MiniStor system complies with all relevant European and national regulations concerning the use, storage, and handling of ammonia (NH₃), particularly EN 378:2016. The system design, including material selection, control strategy, safety instrumentation, and operating procedures, ensures conformity with applicable legislative and safety standards. Certification for the MiniStor was provided by Moody Hellas S.A.

Discussion

The use of ammonia in the MiniStor system was comprehensively assessed in Deliverable D4.6. All relevant European directives—such as the Pressure Equipment Directive (2014/68/EU), the Seveso III Directive (2012/18/EU), and the REACH Regulation—have been considered in the design and validation of the TCM unit. Furthermore, risk assessments were performed for health, environmental, and explosion hazards. Mitigation measures include redundant gas detection systems, pressure relief devices, automatic shutdown protocols, and defined emergency handling procedures. The NH₃ handling protocol during commissioning, operation, and decommissioning was reviewed and approved by Moody Hellas S.A., confirming full regulatory compliance.

KPI_29 Compliance: Container as machinery room

KPI description

Pass/Fail criterion whether the MiniStor system complies with the sections of the European standard EN 378-3 considered relevant to use the TCM container in a machinery room due to the use of ammonia as a refrigerant.

Formula for calculation

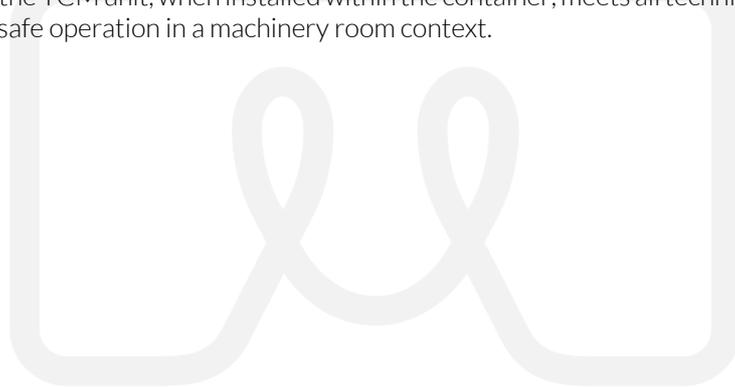
Compliance with European standard EN 378-3 for relevant refrigerant requirement.

Results

The MiniStor TCM container is fully compliant with the relevant sections of EN 378-3 concerning machinery rooms using ammonia-based systems. The design of the MiniStor system has been validated through third-party certification by Moody Hellas S.A.

Discussion

According to EN 378-3, machinery rooms that contain ammonia must fulfil strict safety requirements concerning ventilation, access control, gas detection, alarm systems, and emergency response. As documented in D4.6, the MiniStor container is equipped with high-grade instrumentation, including ammonia concentration sensors (with multi-level alarm thresholds), automatic ventilation and shutdown systems, and remote monitoring capabilities. The structural and functional layout of the container ensures safe isolation from inhabited areas. The conformity assessment by Moody Hellas S.A. confirms that the TCM unit, when installed within the container, meets all technical and regulatory specifications for safe operation in a machinery room context.



KPI_30 Compliance: Planning regulations

KPI description

Pass/Fail criterion whether the MiniStor system complies with the planning regulations that apply for renewable systems and for the installation regional or/and local level as well as national compulsory regulations. In addition, also the overlap with national standards will be investigated.

Formula for calculation

Compliance with the national building and/or energy regulations to get approved installation in the demonstration site from the correspondent authority.

Compliance with the regional and/or local energy and building regulations to be approved for installation in the demonstration site from the municipality or any other authority.

Results

Cork: Pass

The MiniStor unit in Cork (Ireland) complied with all national and regional regulations, no special permissions were required for its installation. The size of the unit including solar field may not be suited to all social housing sites in Ireland because the garden space in social houses in Ireland would not be sufficient in size to contain the MiniStor system. Accessibility to install the system would also be an issue.

Sopron: Pass

Hungarian building regulations require the integration of renewable energy systems in new constructions but do not specify the type or configuration. Technologies such as PV panels, solar thermal collectors, heat pumps, PCM, and TCM—as used in the MiniStor system—are all accepted. The ammonia limit for building installations is 1000 kg, and the MiniStor system operates with significantly lower quantities, thus remaining well within legal boundaries. System integration with the existing heating infrastructure required attention but was implemented without major complications. The system meets the national requirements for building energy performance and has demonstrated reliable operation.

Kimmeria: Pass

The MiniStor system in Kimmeria complies with all relevant national, regional, and EU regulations. No legislation was identified that prohibits or limits the use of ammonia as a refrigerant, provided the system design follows the EU standard EN 378:2016. Since the MiniStor system uses a double indirect loop, no load limits apply.

National legislation concerning the safe use of hazardous gases (Ministerial Decision 136860/1673/§15/2018) requires gas detectors with automatic shut-off functions and adequate fire safety measures. This is fulfilled by the MiniStor system design. Additional wastewater discharge limits (60 mg/L) from another region (Attica) are not applicable in Kimmeria but highlight the need to avoid direct ammonia discharge.

On a regional level, the Technical Services of DUTH confirmed that no additional local restrictions apply beyond EN 378 and the general provisions of Ministerial Decision 172058/2016, which only affect facilities storing more than 50 or 200 tonnes of ammonia—well above the MiniStor system's capacity.

Santiago de Compostela: Pass

All necessary regulatory and administrative requirements were met through close coordination between the project team and relevant university services. A dedicated project team was established, including researchers from CITIUS, technical staff from the USC Infrastructure Management Service, and the director of the residence. The Rector's Office granted all required authorizations for building modifications, system installation, and data processing in accordance with national legislation.

Detailed engineering designs were prepared and approved to ensure full compliance with applicable regulations.

KPI_31 Reduced fossil fuel consumption

KPI description

This KPI quantifies the relative change of the fossil fuel consumption per year before and after the installation of the MiniStor system with respect to the final fuel consumption.

Formula for calculation

$$KPI = \frac{m_{before} - m_{after}}{m_{after}} \cdot 100 \%$$

m_{before} mass of oil-equivalent fossil fuel consumed per year before the installation of the MiniStor corrected for environmental difference

m_{after} mass of oil-equivalent fossil fuel consumed per year after the installation of the MiniStor

Goal: Expected reduction of up to 25% energy consumption assuming an average of 75% of energy coming from fossil fuels. (estimated improvement based on theoretical calculations for MiniStor system)

Results

The calculation of KPI 31 focuses exclusively on heat consumption, as this is the domain where fossil fuels were primarily used in the baseline systems. Electricity is not considered in this assessment, as the impact of MiniStor on electrical energy use is inconclusive and not quantifiable within the current data set.

Since this KPI expresses the relative reduction in fossil fuel use, it can be directly derived from the change in thermal energy demand covered by fossil sources. Assuming that fossil fuels covered the full baseline thermal demand and that all energy savings translate into reduced fossil fuel use, the following simplification applies:

$$KPI_{31} = \frac{m_{before} - m_{after}}{m_{after}} \cdot 100\% = \frac{(Q_{before} - Q_{after})}{Q_{after}} \cdot 100\% = KPI_{13}$$

The result of KPI 31 is therefore numerically identical to the relative thermal energy savings previously reported under KPI 13. The corresponding values can be found in Table 3.

Discussion

KPI 31 assesses the reduction in fossil fuel consumption by evaluating the change in thermal energy demand before and after the installation of MiniStor. Because fossil fuels were the main energy carrier for thermal systems in the baseline scenario, this KPI directly reflects the decarbonisation effect achieved by MiniStor.

To ensure robustness and consistency, the analysis relies on the relative thermal energy savings calculated in KPI 13, which are based on monitored consumption data and the simulation data for comparison. Electrical energy is excluded from the calculation due to inconsistent findings across demo sites.

By aligning the logic with established thermal KPIs and assuming complete fossil-based coverage in the baseline, the results of KPI 31 present a clear indication of MiniStor's contribution to reducing fossil fuel dependency. All demonstration sites achieved reductions of over 25 %, confirming the relevance of the system for climate mitigation. Full details are provided in Table 3.

KPI_32 Reduction of GHG emissions

KPI description

This KPI quantifies the reduction of the greenhouse gas (GHG) emissions per year before and after the installation of the MiniStor system.

Formula for calculation

$$KPI = n_{before} - n_{after}$$

n_{before} mass of CO₂-equivalent emissions of GHG per square meter area and demonstration site per year before the installation of the MiniStor corrected for environmental difference

n_{after} mass of CO₂-equivalent emissions of GHG per square meter area and demonstration site per year after the installation of the MiniStor

Goal: < 31.87 kg CO₂eq/m²/year on average for all demonstration sites (calculated impact from exchange of conventional fossil-based burner to MiniStor solution)

Results

Table 9: Comparison of thermal energy consumption and associated CO₂ emissions before and after MiniStor installation across demonstration sites. Emission factors per energy source are used to calculate site-specific CO₂ footprints.

Demo Site	Energy Consumption before MiniStor (kWh/m ² /year)	Energy Consumption after MiniStor (kWh/m ² /year)	Source	Footprint of the source (kgCO ₂ eq/kWh)	n_{before} (kgCO ₂ eq/m ² /year)	n_{after} (kgCO ₂ eq/m ² /year)
Cork	162.2	79.5	Gas Boiler	0.295	47.85	23.45
Kimmeria	147.5	68.5	Biomass Boiler	0.2	29.5	13.7
Santiago de Compostela	153.3	73.7	Gas Boiler	0.295	45.2	21.7
Sopron	105.2	36	Electric heaters	0.25	26.3	9
				Mean:	37.2	16.96

Discussion

KPI_32 evaluates the annual greenhouse gas (GHG) emissions per square metre after the installation of the MiniStor system, across all demonstration sites. The target value is 37.2 kg CO₂-eq/m²/year, which corresponds to the expected impact from replacing conventional fossil-based heating systems with the MiniStor solution.

Based on energy consumption simulations carried out by IERC and system performance data from EMI laboratory tests, the calculated average GHG emission after installation is 16.96 kg CO₂-eq/m²/year. This emission value is well below the defined emission threshold, confirming that the MiniStor system significantly reduces the operational carbon footprint of residential buildings. The calculation incorporates standard emission factors for different energy sources—electricity, gas, and biomass—as documented by the UK Parliamentary Office of Science and Technology³. While the baseline systems vary across sites, the harmonised methodology ensures comparability and reliability of results.

In conclusion, the KPI target is clearly met. The results demonstrate that the MiniStor system, when implemented under the tested boundary conditions, supports a substantial reduction in site-level GHG emissions and contributes to the decarbonisation of the residential energy sector.

³ <https://researchbriefings.files.parliament.uk/documents/POST-PN-0523/POST-PN-0523.pdf>

KPI_33 Total capital cost per kW installed

KPI description

Expected total cost of the system evaluated in relation to the maximum power in kW.

Formula for calculation

$$KPI = \frac{C_{capital}}{P_{kW}}$$

$C_{capital}$ Capital cost (includes delivery and installation costs) [€]
 P_{kW} Power of the system [kW]

Discussion

While the total capital cost per installed power is a relevant metric to assess the cost-efficiency and competitiveness of energy systems, this KPI cannot be meaningfully assessed at the current stage of the MiniStor solution.

The demonstration systems were deployed as early prototypes and include numerous pre-commercial features, such as integrated TCM storage, custom-built containers, and pilot-specific design modifications. As a result, the recorded capital expenditures are not reflective of expected market conditions and would significantly distort any power-normalised cost analysis.

A meaningful evaluation of this KPI would require cost data from serial production, standardised installation processes, and optimised supply chains, none of which are available at TRL7. For this reason, this KPI is excluded from the current assessment. Future iterations of the system—especially under commercialisation scenarios—may allow for a more robust analysis once reliable market data becomes available.

KPI_34 Reduction in construction costs

KPI description

This KPI measures the relative reduction in the construction cost of the MiniStor system relative to the MiniStor installation costs due to MiniStor solutions: pre-assembled components, AR/VR mounting support and prefabricated system modules. A major challenge in the calculation of this KPI is the estimation of the installation costs without the MiniStor solution because multiple concurrent solutions exist. Here, the costs are estimated based on the installation costs of a comparable system that is supported/exchanged by MiniStor.

Formula for calculation

$$KPI = \frac{C_{conventional} - C_{MiniStor}}{C_{MiniStor}} \cdot 100 \%$$

$C_{conventional}$ Estimated installation costs of the components according to suppliers' estimation to an equivalent power output system.

$C_{MiniStor}$ Installation costs of MiniStor system averaged for each different demonstration sites.

Goal: 20 %

(typical cost reduction in other solutions where the suggested technologies have been employed)

Results

As outlined in Section 3.3 of D7.7, the following installation costs apply:

Table 10: Comparison of Installation costs between MiniStor and Conventional HVAC Systems, including resulting KPI for construction cost reduction.

Demo Site	Installation Cost MiniStor [€]	Installation Cost Conventional HVAC [€]	KPI
Kimmeria	11'000	8'000	- 27.3%
Santiago de Compostela	11'000	10'000	- 9.1%
Sopron	10'000	10'000	0%
Thessaloniki (pre-pilot)	11'000	8'000	- 27.3%

$$Thessaloniki = \frac{8000 - 11000}{11000} \cdot 100 \% = -27.3 \%$$

$$Kimmeria = \frac{8000 - 11000}{11000} \cdot 100 \% = -27.3 \%$$

$$Santiago de Compostela = \frac{10000 - 11000}{11000} \cdot 100 \% = -9.1 \%$$

$$Sopron = \frac{10000 - 10000}{10000} \cdot 100 \% = 0 \%$$

Discussion

The cost comparison presented in this KPI focuses on the four demonstration sites for which reliable and disaggregated installation cost data are available, namely Kimmeria, Santiago de Compostela, Sopron, and Thessaloniki. These figures allow for a direct assessment of the cost impact of the MiniStor system relative to conventional HVAC installations. The highest cost difference was observed in Thessaloniki and Kimmeria, where installation was 27.3 % more expensive. Even in Sopron, the cost was on par with the benchmark, and in Santiago, a slight increase of 9.1 % was recorded.

These results reflect the current TRL7 status of MiniStor and the nature of its deployment as a prototype solution:

- Site-specific adaptations and custom engineering.
- Containerised installations that are not optimised for cost.
- Extended piping and system integration efforts.

However, D7.7 clearly outlines the structural cost-reduction potential of MiniStor in future commercial applications. In particular, savings are expected from:

- Avoiding the use of external containers when buildings offer technical rooms.
- Reducing integration and piping costs through compact layout and standardised system modules.
- Scaling through serial production and industrial prefabrication.

For Cork, no reference costs for a standard HVAC installation are available in D7.7, which prevents a meaningful calculation of the KPI for this site. Nevertheless, given the comparable residential setting and system configuration, it can be assumed that the baseline installation costs in Cork would fall within a similar range as for the other sites (i.e. €8,000–€10,000). However, in the absence of documented data, Cork has been excluded from the KPI calculation.

In conclusion, while no cost reduction has been achieved at the current stage, the MiniStor system has embedded features that support construction cost savings in a higher TRL or commercial context, e.g. through standardisation. This confirms that the KPI target of 20 % reduction remains realistic, though currently not yet realised.

KPI_35 Operational cost (€/kWh)

KPI description

The operational cost is the sum of the costs (O&M, energy consumed, spare parts, etc.) necessary to maintain the system operative.

Formula for calculation

$$KPI = \frac{C_{operation}}{E_{kWh}}$$

$C_{operation}$ Total operational cost during 1 year [€]

E_{kWh} Energy provided by the system during 1 year [kWh]

Results

$$C_{operation} = C_{operational} + C_{maintenance} = 0 + 300 = 300 \text{ €/y}$$

$$E_{produced} = E_{heating} + E_{DHW}$$

Table 11: Annual operational cost per unit of energy at each demonstration site based on simulated thermal output and standardised maintenance assumptions.

Demo Site	Heating	DHW	Total energy	O&M	KPI
	kWh/y	kWh/y	kWh/y	€/y	€/kWh
Cork	3'247	3'996	7'244	300	0,041
Kimmeria	2'783	2'845	5'627	300	0,053
Santiago de Compostela	3'111	3'469	6'580	300	0,046
Sopron	4'223	9'114	13'337	300	0,022

Discussion

The calculation is based on simulation results for energy output at the demonstration sites, combined with operational and maintenance cost assumptions taken from Deliverable D7.7 "Costs and Benefits Assessment". Specifically, the operational cost is defined as the annual sum of maintenance costs and costs associated with system operation, divided by the total annual energy delivered (thermal energy for heating and domestic hot water).

As detailed in D7.7, no energy costs are considered during MiniStor operation, as the required energy is assumed to be fully covered by the renewable generation from the PVT system under standard operating conditions. In situations where renewable energy is temporarily unavailable, the system may rely on backup sources; however, such fallback scenarios are not included in this calculation. As a result, the operational energy cost is assumed to be zero, and only scheduled maintenance costs are included in the numerator.

Table 12: Annual operational and maintenance cost assumptions per system component.

Component	Operational costs [€/y]	Maintenance cost [€/y]
PVT panels	0	150
TCM Unit	0	50
PCM Unit	0	0
HEMS	0	100
Total Maintenance Costs	0	300

As shown in the calculation, the KPI varies across demonstration sites due to differences in annual energy output. Sites where the MiniStor system provides a higher total energy yield result in lower specific operational costs. For instance, Sopron achieved the lowest operational cost at 0.022 €/kWh, due to the highest total energy output. In contrast, Kimmeria showed the highest value at 0.053 €/kWh, due to lower delivered energy under the same fixed maintenance cost.

This KPI therefore highlights the conditions under which MiniStor is more economically favourable. It reflects the system's ability to offset maintenance costs through high energy output. Sites with greater coverage of building energy demand and more continuous operation show improved economic efficiency. However, it should be noted that the current calculation assumes ideal renewable availability, and does not account for backup energy use or unscheduled maintenance events.



KPI_36 Payback period

KPI description

The payback period or Pay Back Time (PBT) is the amount or time necessary to recover the initial investment compared to the generated cash flow. It measures the length of time to reach the break-even point.

Formula for calculation

$$PBT = \frac{C_{capital}}{CF_y} [y]$$

$C_{capital}$ Capital cost [€]

CF_y Annual cash flow [€]

Goal: 6.7 a

(estimated payback period based on estimated energy and cost savings)

Discussion

Although this KPI is highly relevant for assessing market entry potential, it cannot be meaningfully calculated at the current TRL 7 stage. The prototype systems developed within MiniStor are not produced at scale, and the resulting capital costs do not reflect realistic market conditions. Therefore, a reliable estimation of the actual payback period under commercial conditions is not feasible at this stage.

Deliverable D7.7 provides a broader economic assessment that incorporates estimated price acceptance ranges in each participating country. These estimates are based on the assumption of a customer-acceptable payback time, derived from literature benchmarks. Across the target markets, acceptable PBT values are generally expected to lie between 10 and 15 years. These values serve as a reference for gauging future price targets and market feasibility.

KPI_37 Reduction of energy cost

KPI description

The reduction of energy cost defines the difference of cost for 1 kWh of energy obtained with MiniStor (improved scenario) compared to 1kWh without the MiniStor system (baseline scenario).

Formula for calculation

$$KPI = C_{kWh_baseline} - C_{kWh_MiniStor} \left[\frac{\text{€}}{\text{kWh}} \right]$$

In percentage of the baseline cost:

$$KPI = \frac{C_{kWh_baseline} - C_{kWh_MiniStor}}{C_{kWh_baseline}} \cdot 100$$

$C_{kWh_baseline}$ Baseline cost for 1 kWh

$C_{kWh_MiniStor}$ MiniStor cost for 1 kWh

Goal: 30 %

(estimation of efficiency improvement and integration of renewable energies)

Results

The energy costs used in this analysis are based on country-specific electricity and gas prices from the EUROSTAT 2024 database, as reported in Deliverable D7.7. Biomass prices were not consistently available across all pilot countries; where unavailable, the EU average was used. Table 13 provides an overview of the energy vector prices assumed for each site.

Table 13: Pilot's energy vectors average prices.

Demo Site	Baseline system	Electricity price ⁴ [€/kWh]	Natural gas ⁵ price [€/kWh]	Biomass price ⁶ [€/kWh]
Cork	Gas Boiler	0,312	0,1136	0,0204
Kimmeria	Solar + Biomass Boiler	0,2853	0,1169	0,0204
Santiago de Compostela	Gas Boiler	0,2684	0,1004	0,0326 ⁷
Sopron	Electrical heaters	0,1545	0,0472	0,0204

For each demo site, the effective cost of heat generation in the baseline scenario is determined by considering the system's energy efficiency. The calculated cost per kWh in the baseline and MiniStor scenarios is summarised in Table 14, and the resulting KPI values are provided in Table 15.

⁴ <https://ec.europa.eu/eurostat/en/web/products-eurostat-news/w/ddn-20250506-2>

⁵ https://ec.europa.eu/eurostat/statistics-explained/index.php?oldid=636298&title=Natural_gas_price_statistics&utm

⁶ <https://www.baltpool.eu/en/baltpool-biomass-exchange-results-in-2024-market-dominated-by-logging-residue-wood-chips-and-short-term-contracts>

⁷ <https://www.avogadroenergy.com/it/confronto-annuale-del-prezzo-dei-combustibil-19-03-2025>

Table 14: Pilot's baseline costs.

Demo Site	Baseline system	Baseline price considered €/kWh	Efficiency of the system η / COP	Cost baseline €/kWh
Cork	Gas Boiler	0,1136	0,95	0,1196
Kimmeria	Solar + Biomass Boiler	0,0204	0,85	0,0204*
Santiago de Compostela	Gas Boiler	0,1004	0,95	0,1057
Sopron	Electrical heaters	0,1545	0,99	0,1561

* The baseline cost in Sopron takes in consideration an average contribution of 15% from the solar field

Table 15: KPI calculation and results

Demo Site	Cost of Baseline €/kWh	Cost kWh MiniStor [€/kWh]	KPI (absolute value) €/kWh	KPI (relative value) %
Cork	0,1196	0	0,1196	100
Kimmeria	0,0240	0	0,0240	100
Santiago de Compostela	0,1057	0	0,1057	100
Sopron	0,1561	0	0,1561	100

Discussion

The results of this KPI are closely tied to the source of input energy for the MiniStor system. Since the system is primarily powered by renewable energy – specifically, solar energy harvested through the PVT system – the operational energy cost can be considered negligible or zero under standard operating conditions.

The MiniStor system covers both thermal and electrical energy demand using the PVT infrastructure. Even the electricity required to operate internal components such as the circulation pumps, heat pump, and thermal input to the TCM is expected to be sourced from solar power. Consequently, when the system operates under optimal conditions, the cost of delivered energy approaches zero.

This assumption underpins the economic assessment presented in D7.7. The KPI therefore reflects the maximum achievable cost reduction when the system operates without backup energy sources. The results demonstrate that MiniStor can reduce the cost per kWh of heating and DHW by up to 100 % compared to the baseline systems.

However, achieving such performance requires careful system sizing and optimisation of the solar field or other renewable energy sources. Insufficient renewable coverage or suboptimal system integration would reduce the extent of the cost savings.

KPI_38 Internal Rate of Return (IRR)

KPI description

The IRR estimates the profitability of the investment. It represents the discount rate that makes the net present value (NPV) of the cash flows equal to zero.

The Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time.

Formula for calculation

$$KPI = IRR, \text{ such that}$$

$$NPV = \sum_{t=1}^T \frac{NCF_t}{(1 + IRR)^t} - C_c = 0$$

- NPV* Net present value
- NCF_t* Net cash flow during year t
- C_c* Capital cost [€]
- T* Number of years
- IRR* Internal rate of return

The analytical calculation of the IRR is not an easy task. To calculate IRR, it is common to use the NPV formula setting NPV equal to zero and solving the IRR in an iterative way using a spreadsheet tool.

Results

The IRR was calculated based on the additional investment required for the MiniStor system, defined as the difference between the MiniStor CAPEX and the baseline system cost (Deliverable 7.7). The net cash flow (NCF) corresponds to the annual energy cost savings, as calculated for heating and domestic hot water (DHW) provision. The calculation assumes constant annual cash flows over the system lifetime.

Table 16: Internal Rate of Return (IRR) calculation inputs and results for each demonstration site.

Demo Site	Annual cash flow [€/y]	Baseline cost [€]	Additional investment [€]	IRR [%]
Cork	936	21,900	23,100	3
Kimmeria	365	27,400	17,600	-3
Santiago de Compostela	765	21,900	23,100	1
Sopron	2,081	26,400	18,600	14

Discussion

The IRR values reported in Table 16 suggest limited economic return for the MiniStor investment in most sites under the current assumptions, with the exception of Sopron, which shows a comparatively favourable return (14 %). In the other pilot locations, the annual savings were insufficient to offset the higher investment cost within a typical investment horizon.

It must be emphasised that these results reflect a conservative scenario. The calculations are based solely on savings from heating and DHW generation. Benefits associated with cooling operation, demand-side flexibility, avoided peak loads, or future energy price increases have not been considered. Inclusion of these factors would likely improve the profitability assessment.

Accordingly, the current IRR values provide only a partial view of the full economic potential of the MiniStor system. Further analyses with extended cost-benefit boundaries may reveal a more favourable investment profile.

KPI_39 Return on Investment (ROI)

KPI description

It is the economic performance indicator used to evaluate the investment (€) for the MiniStor system, compared to the economic efficiency of an alternative investment. Here, ROI is expressed in percentage of the sum of the net profit generated during its operation, in relation to the total capital investment.

Formula for calculation

$$ROI = \frac{\sum NCF_t}{C_{capital}} \cdot 100 \%$$

NCF_t Net cash flow during the year t

$C_{capital}$ Capital cost [€]

Results

The ROI was calculated based on an assumed initial capital expenditure (CAPEX) of €45,000 for the MiniStor system. The annual net cash flow (NCF) includes savings from reduced energy costs (heating and domestic hot water) and differences in operational and maintenance (O&M) costs between MiniStor and the baseline systems. O&M costs were taken from Deliverable D7.7. For Kimmeria, the O&M cost of the baseline biomass boiler was assumed to be 500€/y⁸, while for Sopron it was considered identical to MiniStor.

Table 17: Annual energy savings, O&M cost differences, and resulting net cash flow (NCF) used for ROI calculation at each MiniStor demonstration site.

Demo Site	Annual Saving from energy [€]	Annual saving from O&M [€]	Annual MiniStor O&M [€]	Annual Cash flow (NCF) [€]
Cork	866	370	300	936
Kimmeria	115	500	300	315
Santiago de Compostela	695	370	300	765
Sopron	2'081	300	300	2'081

Assuming constant cash flow over the years, ROI is calculated over two investment horizons (10 and 15 years) as the ratio of the cumulative net cash flow to the initial investment.

Table 18: ROI calculation over 10 and 15 years using annual net cash flow (NCF) for each MiniStor demonstration site.

Demo Site	Annual Cash flow (NCF) [€]	NCF 10 [€]	ROI 10	NCF 15 [€]	ROI 15
Cork	936	9,362	21%	14,043	31%
Kimmeria	315	3,148	7%	4,722	10%
Santiago de Compostela	765	7,654	17%	11,482	26%
Sopron	2,081	20,814	46%	31,221	69%

⁸ ETA La caldaia a cippato per l'impresa e l'agricoltura - [datasheet](#)

Discussion

ROI is a static performance indicator that does not account for the time value of money. Consequently, the ROI values increase proportionally with the investment period (e.g. 10 vs. 15 years). The results show that the MiniStor system can offer a meaningful return on investment at several demonstration sites. Notably, Sopron demonstrates a strong ROI of 69% over 15 years, driven by relatively high energy savings and favourable baseline conditions.

In contrast, Kimmeria shows a more modest return (10% over 15 years), primarily due to limited annual savings and lower energy consumption overall. While the ROI remains positive, the economic attractiveness of the investment is significantly lower at this site.

Cooling-related benefits were excluded from the calculation due to a lack of reliable data. However, given the hybrid heating-cooling functionality of the MiniStor system, future assessments that include cooling performance could further increase the reported ROI values.

A full comparative analysis including the ROI of baseline systems would provide additional context and should be considered for subsequent market assessments.



KPI_40 Maintenance cost reduction

KPI description

It represents the percentage of reduction of maintenance cost calculated by the comparative analysis of the baseline with an alternative system and the scenario with MiniStor. It can be expressed in absolute value or in percentage.

Formula for calculation

Calculation of KPI from input:

$$KPI = C_{maint,Base} - C_{maint,MiniStor}$$

In percentage:

$$KPI = \frac{C_{maint,Base} - C_{maint,MiniStor}}{C_{maint,Base}} .$$

$C_{maint,Base}$ Cost for maintenance in the baseline scenario.

$C_{maint,MiniStor}$ Cost for maintenance in the MiniStor scenario.

Goal: > 25 % relative change of maintenance costs
(typical reduction of maintenance costs from integration of the chosen technologies)

Discussion

It is not possible to provide a reliable quantitative assessment of KPI 40 at the current TRL 7 stage of the MiniStor system. The estimated maintenance cost of 300 €/year used in other economic KPIs (based on D7.7) is only a rough approximation, as it reflects prototype-specific servicing and does not represent costs for a commercial product.

Similarly, obtaining robust and comparable data for the baseline systems proves challenging. Maintenance costs for conventional systems such as gas boilers, biomass boilers, electric heaters, or solar thermal installations vary significantly depending on unit size, system configuration, and national market conditions. Published literature and market reports provide a wide range of estimates, but these are not directly comparable across countries or system scales relevant to the demonstration sites.

Given these uncertainties on both the MiniStor and baseline sides, any calculation of the maintenance cost reduction would be speculative. For this reason, KPI 40 cannot be calculated with sufficient accuracy at this stage, and no conclusion on potential maintenance cost savings can be drawn until standardised system designs and market-ready cost data are available.

KPI_41 Maintenance frequency reduction

KPI description

This KPI expresses the reduction in the frequency of maintenance interventions with respect to a common system.

Formula for calculation

$$KPI = \frac{(f_{before} - f_{after})}{f_{after}} \cdot 100 \%$$

f_{before} Frequency of maintenance before MiniStor installation

f_{after} Frequency of maintenance after MiniStor installation

Goal: > 20 %

(typical frequency reduction due the integration of the chosen technologies)

Discussion

A reliable calculation of KPI 41 is not possible at the current stage of the project, as MiniStor is still at TRL 7. The systems installed at the demonstration sites are early-stage prototypes, and their limited operational history does not provide a robust basis for assessing the actual frequency of maintenance interventions. Without long-term, real-world operation in a commercial setting, any estimate of maintenance frequency for MiniStor would remain speculative.

KPI₄₂ Energy cost savings in demo sites

KPI description

The reduction of energy cost defines the difference of cost for the annual energy consumption calculated in the pilot site, by the difference between the baseline and the scenario with the MiniStor system. It can be expressed in absolute value or in percentage of the baseline cost.

Formula for calculation

$$KPI = C_{en_base} - C_{en_MiniStor}$$

$$KPI = \frac{C_{en_base} - C_{en_MiniStor}}{C_{en_base}} \cdot 100 \%$$

C_{en_base} Baseline annual energy cost

$C_{en_MiniStor}$ Energy cost in the MiniStor

Goal: 30 %

(estimated cost savings based on theoretical calculations of system improvements due to MiniStor installation)

Results

For KPI 42, only the thermal energy cost is considered. This is consistent with the approach taken in KPI 43 (Reduction of energy consumption), as the results for the electrical demand as discussed in KPI 17 (Electrical energy savings) and KPI 18 (Change in electrical consumption from grid) were inconclusive and not suitable for robust evaluation.

Furthermore, this KPI expresses the relative change in energy costs. Under the assumption that unit energy prices remained constant before and after the installation of MiniStor, the price per kilowatt-hour acts solely as a scaling factor and cancels out in the percentage calculation:

$$KPI_{42} = \frac{C_{en_base} - C_{en_MiniStor}}{C_{en_base}} \cdot 100 \% = \frac{E_{base} - E_{MiniStor}}{E_{base}} \cdot 100 \% = KPI_{43}$$

Had different energy prices been used for the before/after comparison, the result would reflect market fluctuations rather than the systemic impact of MiniStor. To isolate the system's effect, the same price basis is applied for both periods.

As a result, the values for KPI 42 are identical to those reported for KPI 43 and KPI 13 respectively (see Table 3).

Discussion

The results of KPI 42 reflect the relative cost savings attributable to reduced thermal energy consumption, as achieved by the MiniStor system. The exclusion of electrical energy from this analysis ensures that the outcome is not distorted by inconsistent or inconclusive data (see KPI 17 and KPI 18).

By aligning the methodology with KPI 43 and assuming consistent unit energy prices, the analysis isolates the impact of MiniStor on cost-related performance. Several demonstration sites exceeded the targeted 30 % reduction in energy costs, confirming the system's potential for significant thermal cost savings under real-world conditions (see Table 3).

KPI_43 Reduction of energy consumption

KPI description

The KPI is defined as the percentual change of the energy consumption after the installation of the MiniStor system compared to the baseline system behaviour. It can be expressed in absolute value or in percentage of the baseline cost.

Formula for calculation

$$KPI = E_{base} - E_{MiniStor}$$
$$KPI_{relative} = \frac{E_{base} - E_{MiniStor}}{E_{base}} \cdot 100\%$$

E_{base} Baseline annual energy consumption

$E_{MiniStor}$ MiniStor scenario annual energy consumption

Goal: > 25 %

(estimated energy savings based on theoretical calculations of system improvements due to MiniStor installation)

Results

For KPI_43, only the thermal energy consumption is considered, as the analysis of the electric demand as presented in the discussion of KPI_17 (Electrical energy savings) and KPI_18 (Change in electrical consumption from grid) were inconclusive and do not allow for a robust integration of electrical energy into this assessment.

The calculation therefore relies on the results from KPI_11 (Absolute thermal energy savings) and KPI_13 (Relative change in thermal energy net consumption). The values from KPI_13 already express the relative change in thermal energy net consumption, which can be directly applied here. See Table 3.

Discussion

The assessment of KPI_43 focuses exclusively on the thermal component of energy consumption. This decision is based on the fact that the outcomes of KPI_17 and KPI_18, which address electrical energy savings and grid electricity consumption, were inconclusive and did not yield reliable or consistent results across the demonstration sites.

Thermal energy performance, however, is well-documented through the analysis of KPI_11 and KPI_13, where absolute and relative thermal savings could be determined. These results indicate a clear reduction in thermal energy consumption compared to the baseline systems, with several sites exceeding the target of 25 % savings.

By excluding the electrical component, the KPI_43 results provide a conservative but more robust picture of MiniStor's impact on energy consumption.

KPI_44 Energy storage costs (€/kWh)

KPI description

This KPI represents the cost to store 1 kWh of energy with the MiniStor system calculated by the sum of the operative costs (O&M, energy input cost, etc.).

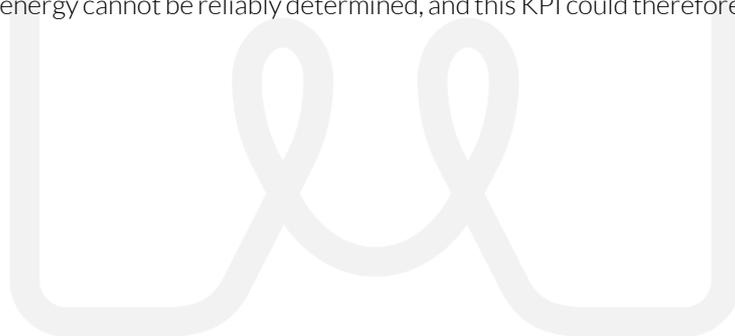
Formula for calculation

$$KPI = \frac{C_{operation} + C_{maint} + C_{energy}}{E_{stored}}$$

$C_{operation}$	Operational cost in considered period.
C_{maint}	Maintenance cost in considered period.
C_{energy}	Cost of energy for the system in considered period.
E_{stored}	Sum of the energy stored in the considered period.

Discussion

This KPI is intended to quantify the cost of storing 1 kWh of energy with the MiniStor system by accounting for operational, maintenance, and input energy costs in relation to the amount of energy stored and later used. However, the available data do not allow for a meaningful calculation. In most cases, MiniStor was not operated for sufficiently long or continuous periods, particularly during the heating season, when storage effects would have been most relevant. As a result, the amount of effectively stored energy cannot be reliably determined, and this KPI could therefore not be evaluated.



KPI_45 Energy Return on Investment (EROI)

KPI description

The energy return on investment (EROI) is the amount of energy expended to produce a certain amount of energy. EROI is central in determining the price of energy.

Formula for calculation

$$EROI = \frac{E_{Out}}{E_{In}}$$

E_{In} Energy input to MiniStor

E_{Out} Energy output of MiniStor

Results

Table 19: Annual thermal energy output and electrical consumption of the MiniStor system with resulting Energy Return on Investment (EROI) per demonstration site.

Demo Site	Annual Energy from MiniStor for heating [kWh]	Annual Energy from MiniStor for DHW [kWh]	Annual energy consumed by MiniStor [kWh]	EROI
Cork	3'247	3'997	1'023	7,1
Kimmeria	2'783	2'845	0	N.A.
Santiago de Compostela	3'111	3'569	176	37,5
Sopron	4'223	9'114	1'114	12

The EROI is calculated by dividing the total annual energy output provided by the MiniStor system (heating and domestic hot water) by the annual energy consumed for its operation. The results for each demo site are summarised in the Table 19.

Discussion

The EROI is a key indicator for assessing the energy efficiency of a technology by comparing the energy delivered to the user with the energy required to operate the system. The results obtained for MiniStor show favourable values across all evaluated sites, with EROI values ranging from 7.1 in Cork to 37.5 in Santiago de Compostela. These results indicate that the system delivers significantly more energy than it consumes, confirming its suitability as an energy-efficient storage and supply solution.

At the Sopron site, the EROI reaches a value of 12, placing it comfortably within or above the typical range for solar energy systems, which is generally estimated between 6 and 16⁹. The exceptionally high EROI in Santiago is attributed to the low electrical consumption of the system during operation relative to its thermal output.

No valid EROI could be calculated for the Kimmeria site, as the energy consumption data for MiniStor is reported as zero. This value is likely erroneous or the result of incomplete monitoring and does not permit a meaningful calculation.

⁹ Carbajales-Dale, Michael & Raugei, Marco & Barnhart, Charles & Fthenakis, Vasilis. (2015). Energy Return on Investment (EROI) of Solar PV: An Attempt at Reconciliation [Point of View]. Proceedings of the IEEE. 103. 10.1109/JPROC.2015.2438471.

KPI_46 Cost of downtimes

KPI description

This KPI measures the financial costs generated by a downtime of the MiniStor system. These costs will be measured based on additional energy costs for operation of the (backup) heating system, maintenance, and repair costs.

Formula for calculation

$$KPI = C_{energy,paid} - C_{energy,Ministor} + C_{maint} + C_{repair} + C_{backup}$$

$C_{energy,paid}$	Cost for energy of backup system during MiniStor outage.
$C_{energy,Ministor}$	Estimated costs of energy for MiniStor system operation if system was not broken.
C_{maint}	Cost for maintenance of system during down time.
C_{repair}	Cost for repair of MiniStor system.
C_{backup}	Cost for temporary installation of a backup system.

Discussion

KPI 46 aims to quantify the financial impact of MiniStor system downtimes. A meaningful evaluation of this KPI is currently not feasible.

As shown in Table 8, the operational time of the MiniStor systems during the demonstration phase was highly variable and, in many cases, limited (median operation time below 35 %). This low availability is attributable to the fact that the systems were implemented in prototype form (TRL 7) and were still undergoing integration and optimisation at several demo sites. Consequently, extended periods of non-operation do not reflect typical system outages, but rather development-related constraints.

Moreover, the cost shares required for the calculation of KPI 46—particularly maintenance and repair costs—cannot be reliably isolated. Most technical interventions were part of broader commissioning, system debugging, or software updates and therefore do not reflect standard repair events. No dedicated costs for temporary backup systems were incurred, as fallback heating solutions were in place as part of the original site infrastructure.

In summary, due to the limited operational continuity of the prototype systems and the non-representative nature of intervention-related costs, KPI 46 cannot be meaningfully calculated at this stage.

KPI_47 Life-cycle cost of energy storage

KPI description

Life cycle cost (LCC) is a KPI that estimates how much money is spent on an asset over the course of its useful life. Whole-life costing covers an asset's costs from the time it is purchased to disposal.

Formula for calculation

$$LCC = C_c + C_{op} + C_m + C_{en_in} + C_{down} + C_d + C_{di}$$

C_c	Capital cost, include delivery and installation
C_{op}	Operational cost
C_m	Maintenance cost (include repair costs)
C_{en_in}	Cost for energy in system input
C_{down}	Downtime costs
C_d	Decommissioning cost
C_{di}	Costs for disposal

Discussion

The life-cycle cost of energy storage can typically be calculated for a product or system that has completed a full operational cycle, or when reliable cost references are available from comparable technology deployments.

At the end of the MiniStor project, the system has reached TRL 7, meaning that only prototyping-level costs are available. Several key cost components required for this KPI—such as installation costs (which vary significantly depending on the building configuration), downtime costs, and end-of-life costs (decommissioning and disposal)—are currently unknown. These values are also highly dependent on the future business model and deployment strategy.

Given the high degree of uncertainty and lack of robust data, a meaningful and representative calculation of this KPI is not feasible at this stage.

KPI_48 Total annual costs

KPI description

The total annual costs are the sum of the annual costs to sustain for the MiniStor system operation (O&M, energy input cost, etc.).

Formula for calculation

$$KPI = C_{operation} + C_{maint} + C_{energy}$$

- C_c Capital cost, include delivery and installation
- C_{op} Operational cost
- C_m Maintenance cost (include repair costs)
- C_{en_in} Cost for energy in system input
- C_{down} Downtime costs
- C_a Decommissioning cost
- C_{di} Costs for disposal

Results

The parameters considered for this KPI are based on the data provided in Deliverable D7.7. The main assumption in this calculation concerns the cost of energy input: energy supplied by the PVT system is considered free of charge. As a result, the only recurring annual cost is associated with system maintenance.

Consistent with the approach applied to other KPIs, the capital expenditure (CAPEX) is assumed to be €45,000, with an expected system lifetime of 20 years. Based on these input values, the Total Annual Cost (TAC) is calculated and summarised in Table 20.

Table 20: Annual total cost of MiniStor system per demonstration site, including depreciation and maintenance.

Demo Site	$C_{depreciation}$ [€/y]	$C_{operation}$ [€/y]	C_{energy} [€/y]	$C_{maintenance}$ [€/y]	KPI [€/y]
Cork	2'250	0	0	300	2'550
Kimmeria	2'250	0	0	300	2'550
Santiago de Compostela	2'250	0	0	300	2'550
Sopron	2'250	0	0	300	2'550

Discussion

The results presented in this section appear slightly above the threshold values typically used for benchmarking similar technologies. However, it is important to emphasise that MiniStor is not a conventional single-purpose system. The capital expenditure (CAPEX) used in this calculation includes several integrated components that are often not accounted for in reference cost tables—such as the thermal and electrical storage units, the Home Energy Management System (HEMS), the PVT collectors, and the cooling subsystem.

Taking these factors into account, the calculated total annual costs can be considered reasonable. The result reflects the multifunctional nature of the MiniStor solution and supports the conclusion that the system offers a competitive cost profile in relation to its broad functionality.

KPI_49 Annuity Gain

KPI description

Annuity (AN) is the incoming or the economic benefits made at the same interval at the beginning of each period (month, year etc.).

Formula for calculation

$$KPI = AN = B - C - C_{cost} \cdot CR(i, T)$$

$$KPI = AN = B - C - \text{Annualised Investment}_{cost}$$

$$\text{Annualised Cost} = \frac{I \cdot r (1 + r)^n}{(1 + r)^n - 1}$$

<i>AN</i>	Annuity gain
<i>B</i>	annual benefits
<i>C</i>	annual costs
<i>C_{cost}</i>	Capital costs at the year zero
<i>Annualised C_{cost}</i>	Capital costs over the Project life
<i>CR(i, T)</i>	Capital recovery factor. It considers an assumed discount rate (i) and the time for the amortization of the investment (T)

Results

- **MiniStor Investment** = 45'000 €
- **Discount rate:** 3% (representative for residential customers)
- **System lifetime:** 15 to 20 years
- **Annuity Factor AN** (for 3 % over 20 years): $= \frac{0,03 (1+0,03)^{20}}{(1+0,03)^{20}-1} = 0.0672$

Table 21: Annualised economic gain per demonstration site based on 3 % discount rate and 15 to 20-year system lifetime.

Demo Site	Annual benefits [€]	Annual costs [€]	Additional investment [kWh]	Annualised investment [€]	Annuity Gain [€]
Cork	1'236	300	23'100	1'553	-616
Kimmeria	615	300	17'600	1'183	-868
Santiago de Compostela	1'065	300	23'100	1'553	-787
Sopron	2'381	300	18'600	1'250	831

Only the additional investment cost (compared to the baseline) is considered. Annualised investment cost is calculated by multiplying the additional investment by the annuity factor.

Discussion

The annuity gain calculation incorporates the capital cost (CAPEX) of the MiniStor system. Although Deliverable D7.7 notes that a market-ready cost cannot be definitively defined at TRL 7, a CAPEX value of €45,000 has been used in several KPI assessments. This amount represents a price level within the range identified for four of the five countries analysed in D7.7. It is assumed that the full investment occurs at year zero. Importantly, only the additional investment cost—i.e. the difference between the MiniStor system and the baseline—is considered in the calculation.

Annual benefits at the demo sites are defined as the cost savings resulting from the portion of energy demand covered by the MiniStor system. Based on these values, three out of four sites currently show a negative annuity gain, suggesting that the investment may not be financially viable under the given assumptions.

However, these results must be interpreted consider the current state of Ministor system as TRL 7. The calculation considers only a subset of the system's total benefits. In particular, contributions from the cooling function and the system's value in providing energy flexibility were not included due to limited data availability. These factors are expected to positively influence the overall economic performance.

Consequently, when considering the full benefit spectrum of the MiniStor system, it is likely that the annuity gain would become positive across all demonstration sites.



3. Conclusions

This KPI assessment report provides a comprehensive analysis of the MiniStor system's performance based on the 49 Key Performance Indicators (KPIs) defined within the project. The evaluation covers technical, operational, environmental, economic, and user-centred dimensions and incorporates measurement data from all five demonstration sites—Cork, Kimmeria, Santiago de Compostela, Sopron, and Thessaloniki (pre-pilot)—wherever data quality and availability permitted. In addition, simulation-based results were used to supplement or replace measurements in cases where monitoring was incomplete, or system operation had not yet commenced.

Across the full set of indicators, the MiniStor system demonstrates a solid performance, particularly with respect to energy savings, system integration, environmental impact, and user satisfaction.

At the same time, the assessment also highlights the limitations that arise when evaluating pre-commercial systems at TRL 7. Notably, several KPIs related to long-term financial performance, life cycle cost, and energy return on investment could not be verified due to the absence of market-ready pricing and operational data covering multiple full heating and cooling seasons. In a few other cases—particularly regarding grid electricity consumption and renewable self-sufficiency—data coverage or consistency issues limited the robustness of the analysis. These gaps were transparently documented, and the underlying methodological decisions were outlined in detail to ensure reproducibility.

The results also illustrate the heterogeneity among the demonstration sites. Differences in building typology, climate, user behaviour, and system configuration have a measurable influence on the outcome of many KPIs. This underlines the importance of context-sensitive interpretations and suggests that MiniStor's real-world performance potential is strongly site-dependent.

Overall, the KPI analysis confirms that MiniStor represents a promising technology solution for decarbonising residential heating and cooling while integrating renewable energy and advanced thermal storage. The results of this report serve as a valuable foundation for further development steps, particularly in preparing the system for large-scale deployment and commercialisation. Future efforts should focus on standardisation, cost optimisation, and robust long-term operation to fully realise the system's potential and improve the KPI outcomes that are currently inconclusive or non-verifiable.