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The EINSTEIN Project and Integrating Seasonal Thermal Energy Storage into the Heating Systems of Existing Buildings

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1. Abstract

This paper gives an overview of the EINSTEIN project, which was established to demonstrate the potential afforded by Seasonal Thermal Energy Storage (STES) when used in conjunction with heat pumps in meeting the needs of energy-efficient buildings. Details are provided of the analysis undertaken in determine the minimum supply temperatures for existing buildings to facilitate the integration of STES-based heating systems.

The acronym EINSTEIN stands for the Effective INtegration of Seasonal Thermal energy storage in ExIsting BuildiNgs. This €9m EU project is funded under the FP7 programme and involves 17 European partners, the lead partner being the Spanish company Tecnalia.

The project ranges from the baselining of STES systems application in existing buildings, the subsequent development of a methodology and an evaluation tool and framework through to the demonstration of the concept in two pilot installations in Spain and Poland.

A key element of the project is to adapt STES to be applied in existing buildings. This involves the integration of existing heating systems (which can have typical operating ranges from 60° C to 80° C) to operate with the significantly lower temperatures associated with STES systems. Thus, an analysis has been carried out to determine the extent to which traditional heating systems can operate effectively with lower supply temperatures whilst still meeting the space heating demands of the dwelling.

Keywords: STES, Seasonal Thermal Energy Storage, Retrofit

2. Introduction

Energy use in buildings accounts for approximately 40% of EU energy consumption. Due to this high energy use, one of the three main targets proposed by the European Economy Recovery Plan in 2008 is "to encourage Energy-efficient buildings, to promote green technologies and to develop energy efficient systems and materials in new and renovated buildings with a view to reducing radically their energy consumption and CO2 emissions".

In order to achieve these objectives, drastic measures are required. The improvement of energy efficiency of conventional generation technologies is not sufficient and a high proportion of energy demand supplied by renewable energy sources is essential. Taking into consideration that heat demand can represent up to 60-70% of total amount of energy consumption in a residential building (1), heating system based on Seasonal Thermal Energy Storage (STES) have the potential to fulfil the objectives established in Europe for energy efficiency in a short timeframe. The fact that the concepts developed within this project are based on innovative adaptation of existing technology is a significant aspect, as it makes possible the development of nearly zero energy buildings (one of the objectives of EPBD directive) within a relatively short timeframe.The overall objective of the EINSTEIN (2) project is the development, evaluation and demonstration of a low energy heating system based on STES concept in combination with heat pumps for space heating and DHW requirements for existing buildings to drastically reduce energy consumption (primary energy savings up to 70% compared to conventional existing thermal systems).

This goal will be achieved by

- Technological developments for STES systems adaptation for existing buildings
- Development of a novel, high-efficiency, cost-effective and compact heat pump suitable for existing buildings and optimized for higher temperature heat sources such as STES systems
- Development of a decision support tool that will help the planners to find the best technology to install in each particular case
- Development of integrated building concept: which passive and/or active measures (insulation, heat recovery, renewables…) and in which order should be applied for an optimized retrofitting

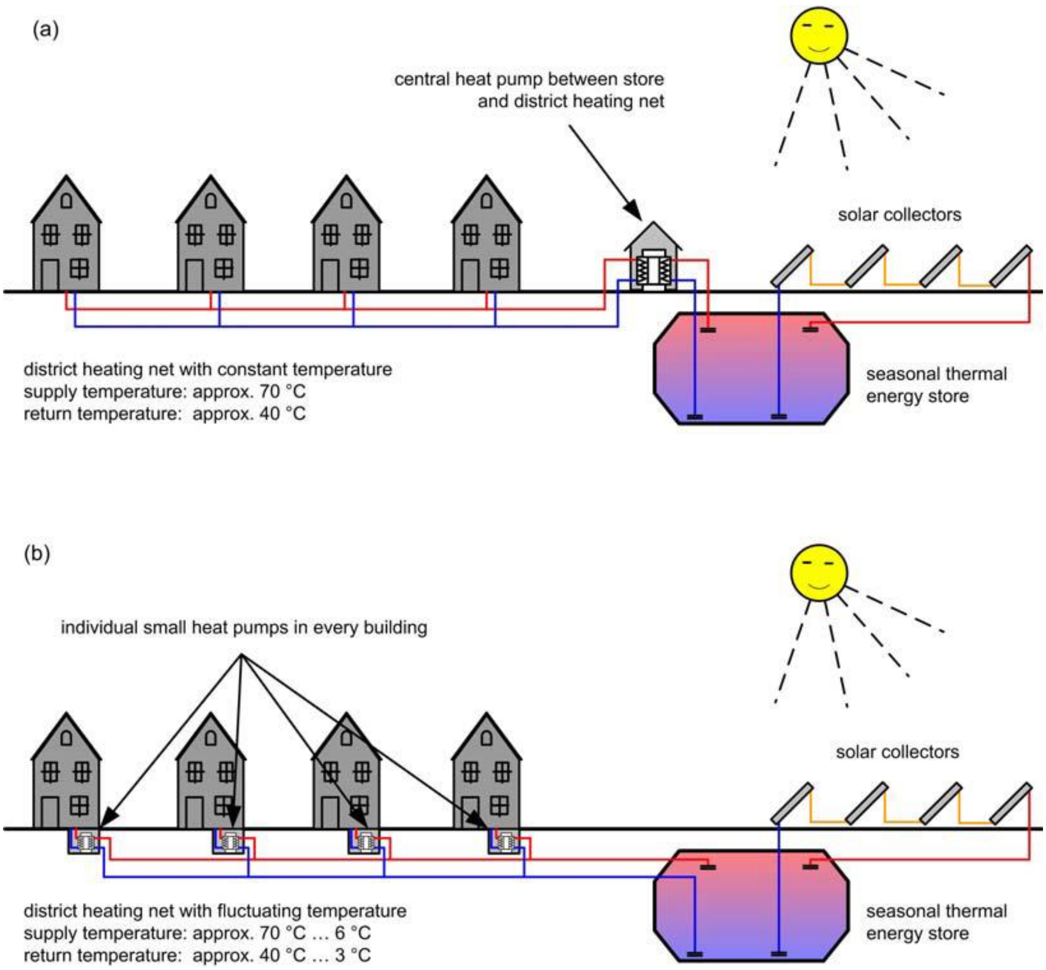

Figure 1 (a) Central heat pump (b) distributed heat pump, in combination with STES

Seasonal Thermal Energy Storage Systems suffer lower losses with the use of low heating system temperatures (e.g. flow temperatures of 40°C). Thus, there can sometimes be a mismatch between the relatively high supply temperatures required by the traditional heating system for optimal system efficiency (e.g. flow temperatures of 80°C for radiators) and the lower temperatures required to optimise the efficiency of the STES based heating system. However, replacing the existing heating system may prove costly, especially in cases where a significant system lifetime remains. Thus, the ability to retain the existing heating system is a desirable element of the overall EINSTEIN project.

Given that the fabric of the building will be upgraded as an integral element of the project in order to reduce the overall energy consumption, it is envisaged that the space heating demand will be significantly reduced. On the other hand, if STES based lower system temperatures are used in the existing heating system, the efficiency of the heating system will be reduced.

Thus an objective of the EINSTEIN project was to determine the extent to which the efficiency of the traditional heating system can be reduced (through reducing the supply temperature of the heating), while still meeting the lower space heating demand of the energy retrofit buildings.

The space heating demands of typical dwellings (with an area of 84.5m^2) located in four regions in Europe were analysed using a TRNSYS model of the dwelling. The four climatic regions considered were:

1. Southern Europe e.g. the climate experienced in Madrid

2. Eastern Europe e.g. the climate experienced in Warsaw
3. Moderate European climate e.g. the climate experienced in Amsterdam
4. Northern Europe e.g. the climate experienced in Stockholm

For each climatic zone, the space heating demand of the modelled dwelling in that region was determined for

1. the base case of the standard dwelling (Reference Building),
2. the same dwelling with a medium energy retrofit
3. the same dwelling with the deep energy retrofit.

The following analysis determines the shortfall in space heating provided by both underfloor heating systems and traditional radiator-based heating systems for varying supply temperatures for each of the climatic zones and retrofit scenarios above. The work has been carried out on the Single Family House (SFH) dwelling model to gauge the impact of the change in supply temperature on meeting the space heating demand.

3. Method

- **Space Heating Demand**

In the EINSTEIN project reference buildings and reference locations have been defined, and a significant number of retrofitting scenarios have been considered. The energy demand reduction potential of each of the scenarios has been evaluated using a TRNSYS model and considered in the context of the cost effectiveness of the various combinations. The optimised medium and deep retrofitting options and resultant annual space heating demands were established (table 1) for the buildings under study.

	Reference {kWh}	**Medium {kWh}**	**Deep {kWh}**
Madrid	15971	5264	3148
Amsterdam	19618	7066	3667
Warsaw	26537	12127	6939
Stockholm	15790	8055	6726

Table 1 Annual Space Heating Demands of Single Family House per Location and Retrofit Scenario

The space heating demands of the reference, medium and deep retrofit buildings have been used for each of the locations in order to gauge the shortfall in meeting the space heating demand caused by sub optimal heating system supply temperatures.

Two different terminal units were used for the purpose of determining the effect of varying supply temperatures, underfloor heating system and radiator system. Each terminal unit model (i.e. underfloor and radiator) has its own characteristics and description procedures and are therefore treated separately and have their own individual TRNSYS models.

Underfloor heating has the advantage of operating at lower temperatures, and therefore provides a better match with the typical STES based temperatures. Nonetheless, it was decided that a sensitivity analysis should be carried out to determine to what extent the supply temperature could be reduced, while still meeting the space heating demands of the dwellings under consideration for each climatic zone.

It is normal to choose a flow temperature of between 45°C and 55°C with a return temperature of 35°C and 45°C in the case of underfloor heating systems (2). Given that the supply temperatures of an STES based system may be lower than these figures, it was decided to carry out analysis based on flow temperatures of 45°C 40°C and 35°C in order to gauge the effects.

Traditional wall mounted radiant heating systems (e.g. cast iron radiators) have a greater market penetration than underfloor heating throughout Europe. For such systems, Hall and Greeno (3) states that typical supply temperatures are 80°C. There is a significant mismatch between the supply temperature of STES based heating systems and that required for optimal operation of the radiators. For the purposes of this analysis, the supply temperatures chosen were 70°C 60°C 50°C and 40°C. In each case the (kWh) shortfall in meeting the space heating requirements were determined and the results presented as a percentage of the space heating demand.

4. Results and discussion

4.1 Underfloor Heating

As previously stated, typical flow temperatures range between 45°C and 55°C for underfloor heating systems. In the scenarios considered the potential for further reducing the flow temperature is considered.

4.1.1 Space heating deficit with no energy retrofit measures

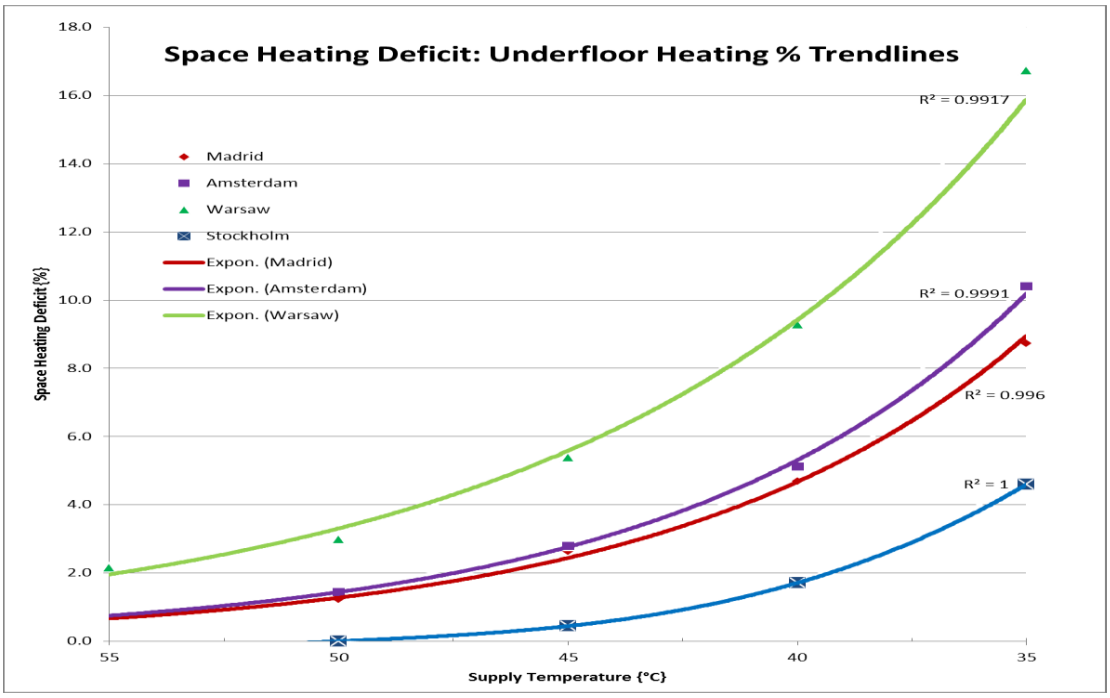

Figure 1 No Retrofit Measures: Underfloor Heating Scenarios

Figure 1 shows the results obtained when using supply temperatures of 55°C, 50°C, 45°C, 40°C and 35°C for the dwellings without any retrofit measures undertaken. The graph shows the percentage deficit at the individual simulation temperatures, along with the associated exponential trendlines for each of the four locations considered.
Analysing the temperatures between 45°C and 35°C (representing a lower than average operating range), the graph shows that the largest shortfall in meeting the space heating demands of the dwelling occurred in the case of the building located in Warsaw.
The shortfall in meeting the space heating demand ranged from 16.7%, to 5.4% (of the total reference building space heating demand). In the case of Warsaw, even at a supply temperature of 55°C, there is a 2% space heating deficit in meeting the space heating needs.
The lowest shortfall occurred in the case of the building located in Stockholm, in which case the shortfall ranged from 4.6% of the space heating demand (in the case of a supply temperature of 35°C) to 0.4% in the case of the supply temperature of 45°C. The minimum supply temperature required in order to meet the space heating demand is 50°C.
For the locations of Amsterdam and Madrid, there is a nominal space heating deficit of 0.7% when the supply temperature is 55°C in the case of the building without any energy retrofit measures and the shortfall between 35°C and 45°C ranges from just under 3% to 10 and 9% respectively.
Thus it is clear that without carrying out energy retrofit measures, the space heating demands will not be met if the supply temperatures are reduced below the normal range for underfloor heating.

4.1.2 Space heating deficit following energy retrofit

Once energy retrofit measures have been undertaken, it is evident that the supply temperature of the underfloor heating system can be significantly reduced.
Simulations have shown that in all cases, the supply temperatures of 45°C, and 40°C were sufficient (to within 0.9%) to meet the space heating demands of the houses which had undertaken both medium and deep retrofitting. In the case of the medium energy retrofit, when the building is located in Warsaw, the shortfall ranged from 0.3% (45°C) to 3.0% (35°C). In all other cases the shortfall was 0.2% or less.
Clearly, even in the case of Warsaw, the shortfall is exceptionally low, and it can be considered that once the houses have had the appropriate retrofit measures undertaken, the flow temperature of the underfloor heating system can be reduced to 35°C, while still meeting the space heating need.
This demonstrates that the characteristics of underfloor space heating closely match the supply temperatures which are provided by the STES based heating systems.

4.2 Radiant heating with traditional radiators

The analysis below was carried out to determine the extent to which the supply temperature of radiant heating provided by traditional radiators can be reduced while still meeting the heating demands of the reference, medium retrofit, and deep retrofit buildings previously described.
For each of the locations under consideration, the annual space heating demand deficits for the building expressed both in kilowatt-hours were determined and a graphical representation is given (Fig 2) showing the space heating demand deficits for varying supply temperature for the reference building, medium retrofit scenario, and deep retrofit scenario.
In figure 2 a trendline is plotted which enables determination of the minimum supply temperature of the heating system which is required to ensure the space heating demands of the building are fully met. In the majority of the cases, a quadratic trendline was used. In all cases the R^2 error of the trendline is 98% or better.

The temperature at which the space heating deficit is reduced to 0 for each of the three retrofit options discussed for the dwellings located in Madrid, Amsterdam, Warsaw and Stockholm is seen from figure 2.
For example, considering the reference building located in Amsterdam, by graphing the space heating deficit at 70°C, 60°C, 50°C and 40°C and plotting a quadratic trendline, it is seen that when the deficit reaches 0 kWh, the supply temperature is at 73°C. Thus in order to fully meet the space heating demands of the dwelling prior to retrofit, the supply temperature must be 73°C or above.
In the same manner, it is seen that the supply temperature must be 59°C or above for the space heating demands to be fully met in the dwelling which has had a medium energy retrofit.
It is also seen that the space heating demand is fully met when the supply temperature is 54°C or above for the house once it has undergone a deep energy retrofit

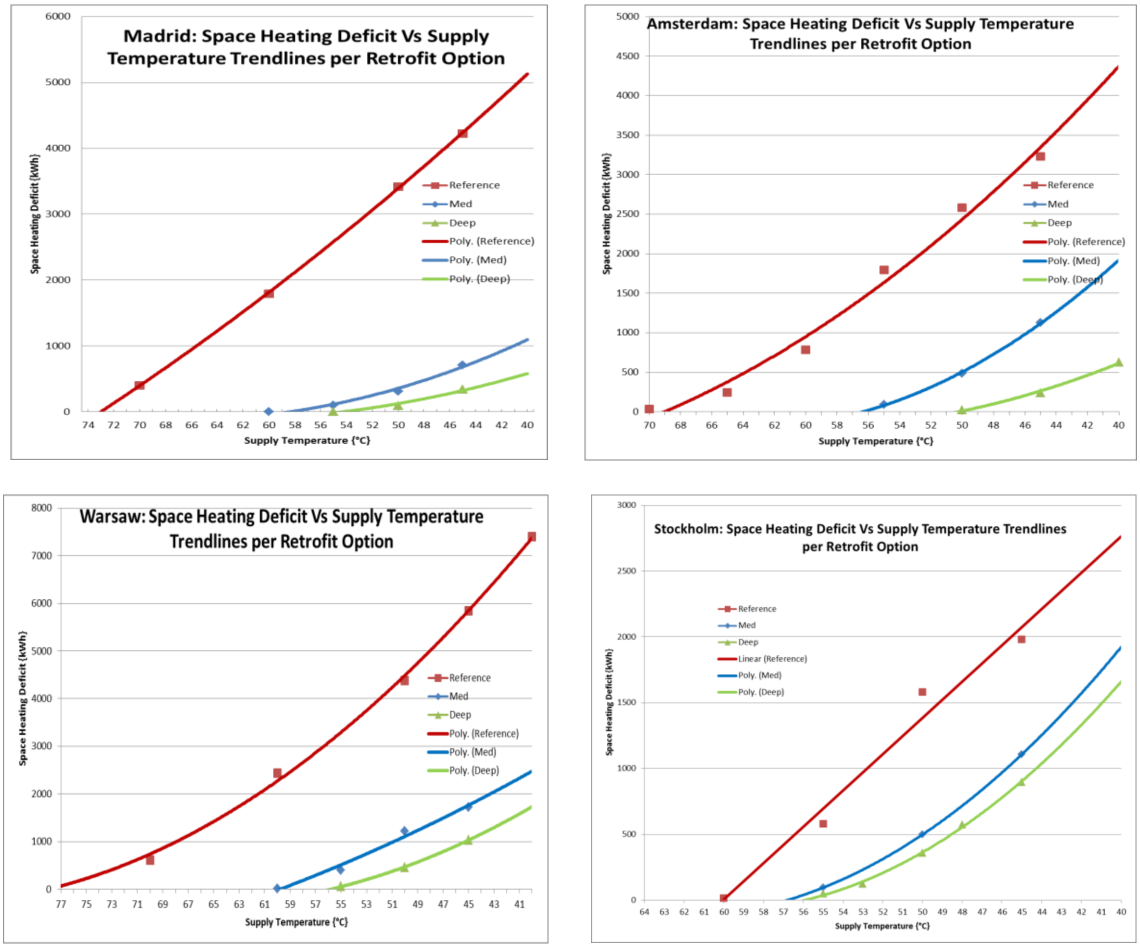

Figure 2 Space Heating Deficit Trendlines for Madrid, Amsterdam, Warsaw and Stockholm

In the same manner, the minimum supply temperatures for each of the dwelling scenarios was determined and is summarised in table 3 below.
Table 3 shows that in all cases (apart from Stockholm), the supply temperature must be 69°C or above in order to fully meet the space heating demand. In the case of Stockholm, the supply temperature must be 60°C or above in order to meet the space heating demand.
However it is clear that supply temperatures can be reduced considerably once the energy retrofits have been carried out. For the medium retrofit scenario, the average required supply

temperature reduces from 70°C to 58°C, and in the case of the deep retrofits the average required supply temperature reduces to 54°C

Location	**Minimun Supply Temperature Required for each Retrofit Scenario {°C}**		
	Reference	**Medium**	**Deep**
Madrid	73	59	54
Amsterdam	69	56	50
Warsaw	77	60	55
Stockholm	60	57	56
Average	70	58	54

Table 3 Minimum Supply Temperatures Required to Meet Space Heating Demands

For all climates, the supply temperature can be reduced to 60°C in the case of the building where either the medium and deep retrofits have been carried out, while still meeting the space heating demands of the dwellings. In the case of Amsterdam it can be reduced to 56°C.
The analysis shows that when the supply temperature is reduced to 50°C, the space heating shortfalls for the medium energy retrofit scenario are typically 5% to 6%, with the exception of Warsaw (where it is 10% at 50°C for the medium retrofit scenario).

Location	**Space heating shortfall for the deep Retrofit Scenario {%}**		
	55 °C	**50 °C**	**45 °C**
Madrid	0.2	2.9	10.7
Amsterdam	0	0.7	6.5
Warsaw	0.9	6.5	14.9
Stockholm	0.7	5.3	13.3
Average	0.4	3.8	11.3

Table 4 Space Heating Shortfall for varying Supply Temperatures, Deep Retrofit Scenario

Table 4 summarises the key findings for the case of the deep retrofit scenario. In all cases the supply temperature can be reduced to 55°C, while still meeting the space heating demands of the dwelling (to within 1%). When the supply temperature is reduced to 50°C the space heating shortfalls for the deep retrofit average 3.8%. It is noted however that in the case of Amsterdam, the space heating demand can be met (to within 1%) with the supply temperature of 50°C.
When the supply temperature is reduced to the lowest considered of 45°C the shortfalls range from 6.5% to 14.9%, with an average shortfall of 11.3%.
It is evident that there is considerable variation in the combination of supply temperature and retrofit required in order to meet the space heating demands for the buildings climates under study. Thus, while general conclusions are evident, simulations need to carried out for the specific case under consideration.
In practice, if a suitably sized radiator cannot be sourced, radiators are oversized rather than undersized to ensure that the space heating demand is met. Therefore, considering that traditional radiators are commonly over sized, there may be potential for using the existing radiators with lower temperatures, thereby decreasing efficiency, but still meeting the reduced

space heating demands of the upgraded dwelling. This may provide further scope for the use of the existing heating infrastructure in meeting the reduced space heating demands of the upgraded dwellings, but needs to be assessed on an individual basis.

5. Conclusions

This analysis has shown that there is potential to reduce the supply temperatures of underfloor heating systems to 35°C while still meeting the space heating energy demands of houses which have undergone medium and deep energy retrofits across the four European climatic zones considered.

It is also shown that there is scope for reducing the supply temperature of traditional radiators from the design temperature of 80°C to 60°C and still meet the space heating energy demands of buildings which have undergone a medium energy retrofit. In the case of buildings which have undergone a deep energy retrofit the supply temperature can be reduced to 55°C whilst still meeting the space heating demand (to within 1%). In addition, it is possible to fully meet the space heating demands in certain circumstances (eg deep retrofit scenario in Amsterdam) with supply temperatures of 50°C.

However, given the variances evident in the analysis undertaken as part of this task, it recommended to accurately model the specific building and heating system under consideration to determine the extent to which the flow temperature can reduced. The analysis as part of this task indicates that in general the space heating deficit increases significantly for supply temperatures below 50°C for traditional radiator systems.

Overall the study has highlighted the suitability of underfloor heating for STES based heating systems. Further it has shown that for dwellings with legacy radiators heating systems, case-by-case analysis is required to match the temperatures found in STES heating systems with appropriate energy retrofit measures for the relevant climatic zone. With one exception, in the cases considered, irrespective of the energy retrofit measures undertaken, radiator heater systems were not able to meet the space heating demand at supply temperatures below 50 °C.

6. Acknowledgements

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7. References

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