Final report

1.1 Project details

Project title	**ELEC-TO-HEAT**
Project identification (program abbrev. and file)	**Journalnr.: 64017-0567**
Name of the programme which has funded the project	EUDP-sekretariatet, Energistyrelsen Niels Bohrs Vej 8D DK-6700 Esbjerg
Project managing company/institution (name and address)	Suntherm ApS, Østergaardsvej 6, DK-7840 Højslev Project leader: Morten Veis Donnerup, mvd@suntherm.dk
Project partners	Danish Technological Institute Gregersensvej 1, DK-2630 Taastrup Technical University of Denmark (DTU Byg) Brovej, Bldg. 118, DK-2800 Kgs. Lyngby
CVR (central business register)	Suntherm ApS CVR: 36 43 92 46
Date for submission	September 30th, 2020

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ELEC-TO-HEAT – Final report

1.2 Short description of project objective and results

English version

Object and focus point of the project has been to further develop and refine a heating system with heat pump and integrated thermal energy storage, ideally suited for the energy system of the future. With heat pumps gaining ground, both politically and commercially, as a preferred heat source for individual residential buildings, a storage capable of storing the heat with minimal losses is of the highest importance. The project has researched, analysed, and defined the ideally suited heat pump including refrigerant, refrigerant circuit, and heat exchanger; heat storages with different PCM materials have been investigated and the best suited heat storage design and PCM-material for the storage tank have been chosen. After having conducted full scale experiments of the complete heating system, simulation models (TRNSYS) have been validated. Three complete SmartHeat systems have been installed with individual consumers, and since measured. In addition, the simulation model has been further developed to handle larger buildings.

The research of the project and its results have validated and refined the heat pump system. The unique combination of heat pump and the integrated storage gives Suntherm a head start in the market for space heating, both in its own business, Heating as a Service, but also as a technology provider as well as a sub-supplier to energy companies and to grid operators.

Danish version

Projektet har haft fokus på videreudvikling og optimering af et varme-system med integreret varmelager, målrettet fremtidens energikilder. Varmepumper vinder frem, både markedsmæssigt og politisk, som varmekilde til enfamilieshuse, hvor et varmelager med minimalt tab af varme er essentielt. Projektet har analyseret den optimale varmepumpe samt kølemiddel, kølekreds, og varmeveksler; varmelager med forskellige PCM-materialer er blevet undersøgt og det bedst egnede materiale til varmelageret valgt. Test af det fulde varmesystem er blevet gennemført, og et simuleringsværktøj er blevet valideret. Tre (3) SmartHeat anlæg er blevet installeret hos tre forbrugere og efterfølgende målt. Derudover er simuleringer for større bygninger gjort muligt.

Projektet har videreudviklet varmesystemet. Den unikke kombination af en varmepumpe med et integreret varmelager gør, at Suntherm kan være et skridt foran konkurrenterne på markedet for varme til bygninger, både inden for sit eget forretningssegment, varme på abonnement, og som teknologileverandør og underleverandør til energi- og netselskaber.

1.3 Executive summary

The development of the heating system consisting of an air-to-water heat pump with an integrated storage and intelligent steering, ideal as a heat source for individual residential buildings, was the core issue of the project. As a result, the ideal heat pump was chosen, the optimal storage tank system with PCM material designed, and a simulation model for sizing and validation developed. Three Smartheat systems installed with private families provide real life validation. Further potential lies in the adaptation for larger buildings and clusters of buildings.

Project results are especially important in to-day's political and environmental climate, giving Suntherm unique advantages in the Danish market for heat pumps, both as a provider within 'Heating as a Service', but also as a technology provider and sub-supplier to electricity companies and grid operators. The adaptation for larger buildings contains perspectives for grid managing.

1.4 Project objectives

The overall aim of the project was to develop a heating system with integrated energy storage. The objective was to a) improve the design of the heat pump and its technology as well as b) determining the best heat storage unit and, specifically, refine and optimize the combination of the two. With the heat storage, the heat pump can be controlled to be in operation in periods without risk of overloading of the electricity grid. This is also an advantage for the operation of the electricity grid itself – hence making the system of interest to the energy companies and energy grid-managing companies, as they may avoid investments in the grid to live up to higher electricity demands.

With experts from the Technical University of Denmark, DTU, and The Danish Technological Institute, DTI, the project has made research within the individual technical areas described in the project proposal as well as combing their research and results in order to obtain the most efficient, combined heating and storage system.

Suntherm/Alpha Innotec heat pump installed with local customer in Salling, Jutland, outside unit and inside storage and steering

<u>First hurdle and change of course – commercially available heat pump</u>

During the first phase of the project, it was decided to adapt the original wish to work with a heat pump built by Suntherm to working with an already commercially available heat pump. The decision was based on the theoretical and practical investigations of the heat pump at the Technological Institute (see Annex: *Teoretisk undersøgelse af varmepumpe. WP4. By DTI.* and Annex: *Laboratorieforsøg med luft-til-vand-varmepumpe med propan som kølemiddel. WP 4. By DTI.)*

The heat produced by the heat pump is transferred to the heat storage, the storage being the core of the system and - business – model. Hence, the decision to use an already available heat pump makes sure that the heat pump itself may, when environmentally and financially feasible, be exchanged with more efficient heat pumps. In order to reducing climate impact due to a possible leak of refrigerant and living up to all legal requirements, it was decided to base the new system on an air-to-water heat pump with R290 (propane) as refrigerant with its GWP of 1.

The heat pump

A theoretical analysis of the heat pump concept was carried out with the aim of deciding the best option measured in efficiency, capacity, operational reliability, environmental aspects, and price.

The analysis looked into relevant refrigerants and the efficiency (COP) obtained. The analysis showed no significant difference in the performance and efficiency of each refrigerant, with one single exception. Hence, environmental considerations, availability, and price stood at the core of the decision.

Propane has good thermodynamic qualities, securing a high COP as well as low global warming when released in the ambient in case of failure. A mono block heat pump that only contains refrigerant in the outdoor unit was chosen.

Results from the analysis are presented in Annex: *Teoretisk undersøgelse af varmepumpe. WP4. By DTI.*

The chosen heat pump was analyzed in a series of tests, also done at the Technological Institute. The efficiency and heating capacity of the heat pump was measured at various surrounding temperatures reflecting Danish climate conditions, and the key output was that the heat pump can produce and forward an adequate temperature, capable of heating the storage with PCM material, and doing so at all outside temperatures with a satisfying COP.

The defrost strategy of the heat pump works well, and tests were made to evaluate possible energy savings for defrosts by using hot water from the tank, trying to establish the optimal interval between defrosting. This is an aspect that could be researched further, keeping in mind the costs for establishing necessary, extra connections.

All tests have shown a satisfactory correspondence between the lab results and the information given by the manufacturer. This is relevant for using the product information in the TRNSYS-model (see below).

The tests are described in *Annex: Laboratorieforsøg med luft-til-vand-varmepumpe med propan som kølemiddel. WP 4. By DTI.*

Design of the heat storage

During the same time, work on and testing of the optimal heat storage tank was done as part of the development process. Various designs for the heat exchange were considered and reviewed and refined with input from all project partners.

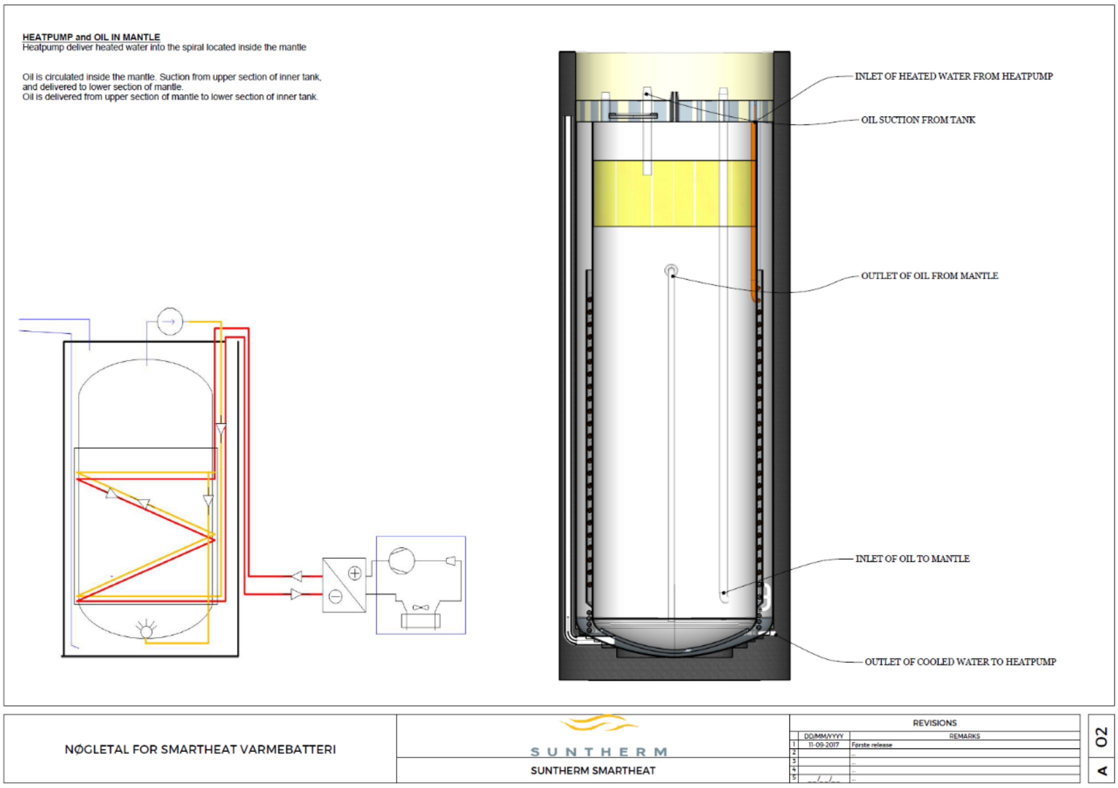


Figure 1: Illustration of the original design of tank-in-tank.

The original thought was to use heat transfer oil as a heat transport medium, and a tank-in-a-tank with the oil in direct contact with the PCM was tested. Due to difficulties keeping the various media segregated, a tank with oil circulated along micro-channels was tested. Microchannels had good transfer qualities but demanded very high energy consumption for running the relevant pumps. Also, heat exchangers with water as transmission medium and PCM was evaluated, and, finally, encapsulated PCM-materials were evaluated and chosen for the storage.

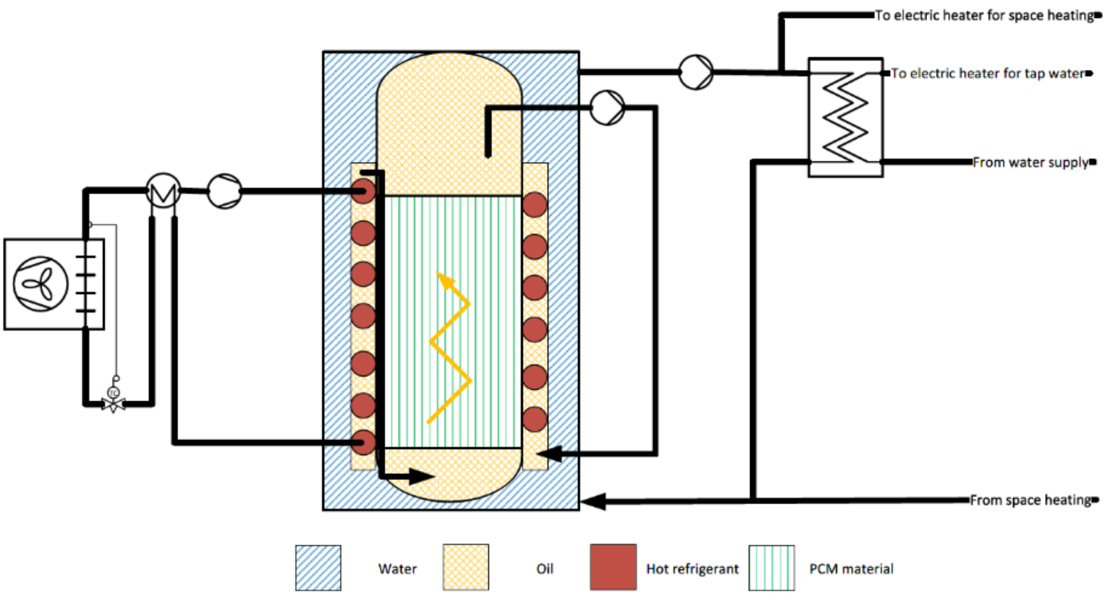


Figure 2: Basic drawing of mantel tank-in-a-tank

The project group evaluated the complexity of the first options to outweigh the reduced storage capacity of the final option with encapsulated PCM-materials resulting in a relatively simple heat storage design.

A note describing the steps of this development process - Note about MPE channels in the PCM buffer - is enclosed. (see: Annex: MPE-vekslere i PDM buffer. WP 1. By DTI.)

Simultaneously, it was important to look into necessary insulation of the heat storage tank. With average Danish temperatures and possible placing of the tank outside, various scenarios for having a tank outside, partly dug into the ground or completely dug into the ground, were considered with a view to insulation of the tank itself. Also, legal requirements to such a tank and/or system must be met. A report describing various scenarios with degrees of insulation for different tank/storage sizes, their calculated heat loss depending on their exact placement and on the variety of connection pipes, made the obstacles in designing a new tank from scratch clear. The conclusion of these investigations clearly supported using PCM-materials in the heat storage.
(see: Note about Insulation of a tank inserted in the ground – Annex: Krav til isolering af nedgravet lagerbeholder. WP 1. By DTI.)

<u>Construction of redesigned unit</u>

Concurrently, at Suntherm's work shop, redesigned units were assembled and delivered to DTU and DTI for testing. Concrete findings from the work at DTU and DTI were taken into account, as an example the flow direction through the tank from bottom to top was implemented.

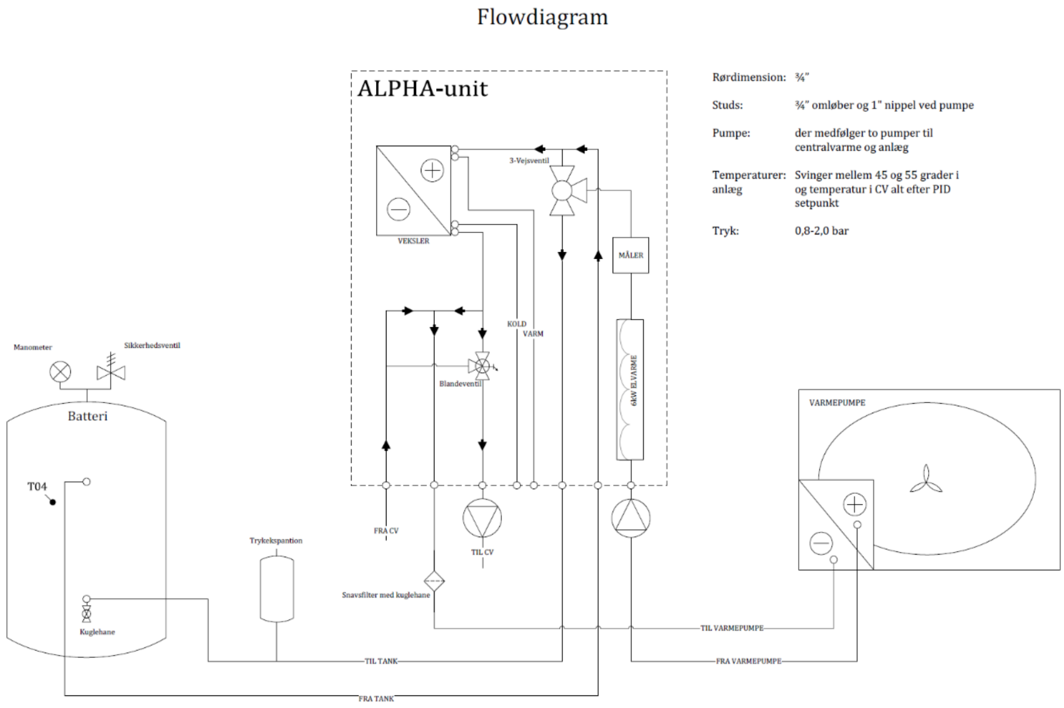


Figure 3: Schematic diagram of the heating system

Figure 4: Before and after installation.

On-going work at Suntherm's workshop

Determining new PCM

Heat pump systems with PCM (Phase Change Material) heat stores for space heating and domestic hot water supply requires PCMs with melting points between 45℃ and 60℃. Two candidates for PCM heat storage material were considered. Sodium thiosulfate pentahydrate, $Na_2S_2O_3{\cdot}5H_2O$ with a melting point of 48℃ and sodium acetate trihydrate, $NaCH_3COO{\cdot}3H_2O$ with a melting point of 58℃. Both are incongruently melting inorganic salt hydrates. Inorganic salt hydrates have high densities compared with organic compounds resulting in a high storage density per unit volume. Both salt hydrates are harmless and relatively inexpensive. The heat of fusion and density are given in the table. The heat content per volume of the two salt hydrates are almost the same in the same temperature interval.

Material	Melting point, ℃	Heat of fusion, kJ/kg salt hydrate	Density at 20℃, kg/m^3 salt hydrate	Heat of fusion, MJ/m^3 salt hydrate
$Na_2S_2O_3 \cdot 5H_2O$	48	209	1740	364
$NaCH_3COO \cdot 3H_2O$	58	265	1450	384

Both salt hydrates melt incongruently, which can cause phase separation and reduction of the heat content of the material as well as a poor long-term stability of the materials. The phase separation problem can, however, be solved by adding additives to the salt hydrate. The additives also change the heat content and the melting point of the materials somewhat.

Heat storages with two PCM materials based on the abovementioned salt hydrates with additives and melting points of about 50℃ and 58℃ were tested by means of laboratory tests. The thermal performance of the two heat storages are similar. Based on a somewhat higher efficiency for the heat pump at a low temperature level of the heat storage than at a high temperature level, the PCM with a melting point of 50℃ was chosen.

See Annex: Analysis of new redesigned unit – Storage. WP5. By DTU.

<u>Simulation model</u>

During the project, a simulation model for the heat pump including the PCM storage was developed and validated. The aim was to develop a simulation tool for right sizing and design of future installations with heat pump and thermal storage. As the energy consumption and technical installations of single family houses vary significantly, one size will not fit all. To our knowledge, no standard tools exist for the combination of a heat pump and a PCM based heat storage, so it was decided to use the open source development software TRNSYS.

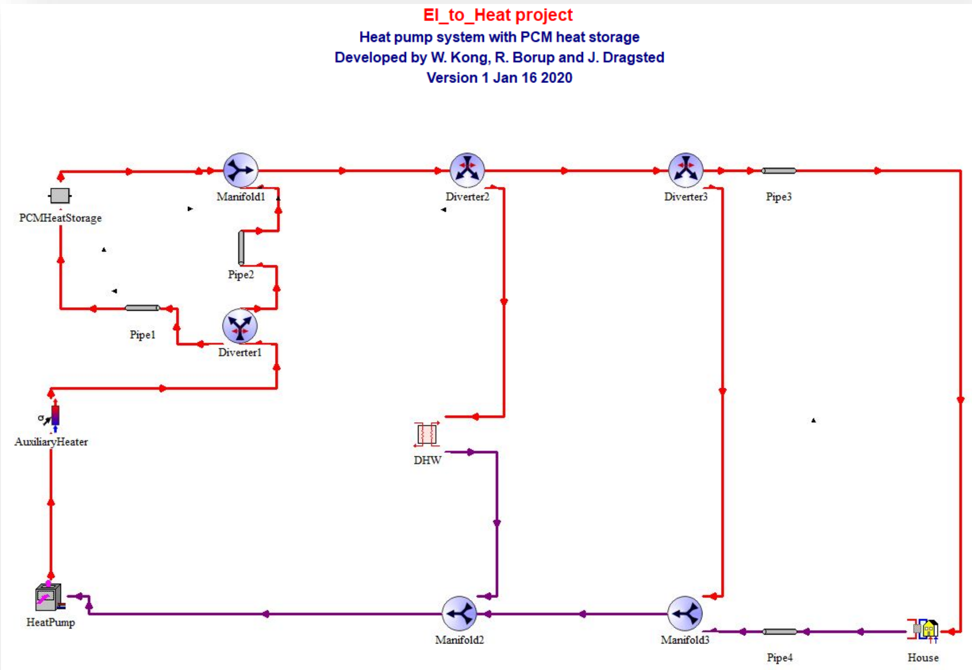


Figure 5: Illustration from TRNSYS model developed in the project

This dynamic software was originally developed at University of Wisconsin for solar energy system simulation but has been expanded with several new component models. However, a thermal storage component had to be completely developed from scratch due to the innovative and new design of the Suntherm PCM storage. DTU was responsible for this part of the project, while DTI took in hand the overall program structure.

The heat production and heat consumption parts of the simulation model have been verified and validated. The consumption part is compared with 3 different and individual single-family houses equipped with Suntherms heating system and shows good consistency. Also, the heat production part of the model is validated for two different sizes of heat pump (measured on heating capacity and efficiency) and the accuracy is within the scope of the project.

The model can thus be utilized by Suntherm and other users to investigate how different control strategies and changes in the heating systems affects their business case and comfort level in the house. Both on existing and future systems including dimensioning of the different components. With this simulation tool the most energy efficient way of controlling the heating system including heat pump and thermal heat storage can be identified as of benefit to the environment.

One of the field test houses in Lolland, before and after installation

The simulation model is also able to simulate the performance (comfort level, costs and efficiency) of a heating system including heat pump and thermal storage for larger buildings, such as schools, kindergartens, clustered residential areas etc.

Please see Annexes: ELEC-TO-HEAT: Simulation model. WP2-WP6. BY DTU and DTI. and Annex: ELEC-TO-HEAT: Analysis of data from field test of redesigned system. WP8.

1.5 Project results and dissemination of results

The relevance of the project has only increased during the project period. The results stemming from the project give Suntherm a head start on the competition. A stable heat storage system that can be used actively and controlled towards production at times with either low electricity prices and/or electricity surplus in the grid makes a huge advantage towards regular heat pump systems.
(*See Annex: Note om Udnyttelse af varmelager og variable el-tariffer.* By Suntherm).

At project beginning, the heat storage had been tested at a low TRL level and was not yet ready for production. The project succeeded in developing the construction in such a way that the complete product is not significantly more expensive than a standard heat pump. The demonstration systems have given Suntherm valuable knowledge about how to optimize the operation of the combined heating system – at the same time as consumer prices become more volatile. The choice of PCM and the use of a heat pump already available on the market partly gave a leaner construction process. However, there is still potential in further optimization of the system's internal connections. Certainly, the project has led to installation of more mature heating solutions with Suntherm's latest customers.

The project realized its objective of optimizing the storage system and paved the way for a simulation model to be used for calculating energy demands for single family housing. A wider perspective of the simulation model would be its use for larger buildings or clusters of buildings.

The Project has assisted Suntherm in positioning itself in a market where new political measures within the energy sector support a broader launch of heat pumps in general, hence giving Suntherm's combined heat storage solution even better market perspectives.

Since project start, Suntherm has increased its staff from consisting of 4 persons to now 10 employees who take care of the full value chain from buying, production, installation, and service.

Most importantly, the increased maturity of the heating solution with the integrated storage has given Suntherm access to energy providers and grid operators; Suntherm's role towards these would be as a technology provider and/or as a sub-supplier.

Export to Denmark's neighboring countries is still a goal. The German market has been difficult to enter and first contacts had not developed. However, new dialogues with larger energy companies about introduction in the German market have opened. As the Danish market conditions have changed significantly during the final year of the project, especially due to political emphasis on green energy solutions and financial subsidies making these solutions available to a wider range of customers, business focus – currently – stays at the Danish market, where a large growth in the market is expected.

Dissemination

Knowledge about the project and its ongoing research has been shared by Suntherm at some major energy conferences ("Energilagringsdagen" in December 2019; "High TechSummit conference" at DTU in October 2019).

Suntherm is currently offering the SmartHeat system commercially to 'heating as a service' providers.

An article (not peer reviewed) about the project and its findings aimed at non-scientists has been written and accepted by two Danish sector relevant journals – 'HVAC' and 'Kulde'. (see Annex: ELEC-to-HEAT. El til varme på en ny måde. Af Ivan Katic, Rasmus Borup, and Claus Schøn Poulsen, DTI.)

A scientific article (peer reviewed) "Investigations of heat pump/PCM heat storage system for the future energy system" is being finalized and will be submitted for publication shortly. Written in co-operation between DTU and DTI.

A sub-site to Suntherm's homepage had been set up, www.suntherm.dk/elec2heat, however with limited activity. Basic information about Suntherm's participation in the project has been shared via Suntherm's own website.

Further, the project results have been presented to students at the Technical University of Denmark following courses on solar heating and energy storage.

1.6 Utilization of project results

Suntherm's Business plan has been updated. Through the simulation model in this project, Suntherm is able to offer to its clients – to end consumers – a matured and thoroughly tested heat system consisting of a heat pump with integrated storage and intelligent steering.

The research done by project partners suggests that further research within the area of steering strategies, further development of the TRNSYS model, and possibly a next level of the heat storage with more in and out-lets and focus on the layering of materials could be of value and further support green strategies.

Also, the prolongation/amendment to the project made it possible to work further with the TRNSYS-model and make simulation of larger buildings. With a tool that will provide an opening towards delivering SmartHeat solutions scaled and aimed at larger buildings, a new business segment opens.

Certainly, the project has supported paving the way and giving knowledge of interest to some of the larger energy companies, who now see Suntherm as a technology provider to them.

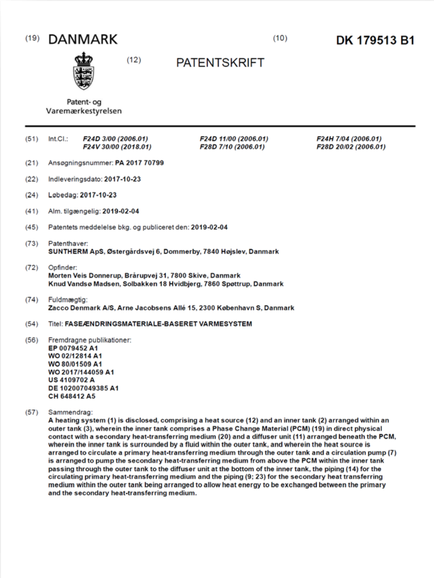
These two areas, solutions for larger building/clusters of buildings and contacts via energy companies to their already existing pools of customers, broadens Suntherm's market potential significantly. Also, in Denmark the politically decided goals within the energy sector only underline the importance of the smart heating solutions.

At the same time, the political climate and the possible subsidies for installing lasting energy solutions broadens the competition, as the subsidies may, in general, make heat pump solutions financially available to a wider range of customers. In this aspect, the necessary qualifications and certifications of Suntherm and its employees is ongoing, in order to be able to fulfill all legal requirements. Suntherm's advantage, however, remains: the integrated heat storage.

Suntherm was eager to explore the German market. This has shown quite difficult, as structures – both political and in terms of crafts, skills, and permissions to install heat pumps – vary significantly from Denmark. Suntherm's first contacts in Germany have not given valuable feed back. Hence, the current decision is to concentrate on the Danish market.

Patents

During the early phase of the project, a patent for the 'tank in a tank'-concept was applied for and given. However, this concept later proved too complex to realize.



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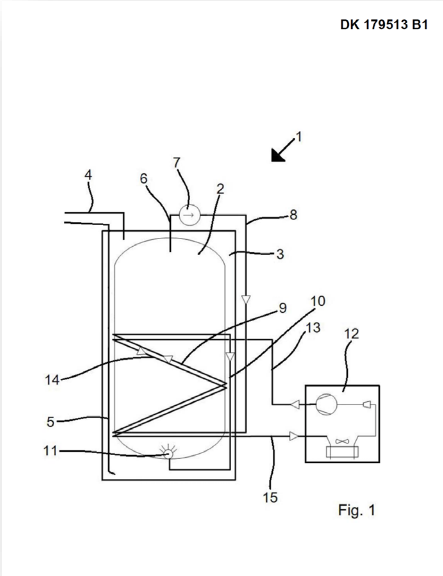
US 4109702 A
DE 102007049385 A1
CH 648412 A5

(57) Sammendrag:
A heating system (1) is disclosed, comprising a heat source (12) and an inner tank (2) arranged within an outer tank (3), wherein the inner tank comprises a Phase Change Material (PCM) (19) in direct physical contact with a secondary heat-transferring medium (20) and a diffuser unit (11) arranged beneath the PCM, wherein the inner tank is surrounded by a fluid within the outer tank, and wherein the heat source is arranged to circulate a primary heat-transferring medium through the outer tank and a circulation pump (7) is arranged to pump the secondary heat-transferring medium from above the PCM within the inner tank passing through the outer tank to the diffuser unit at the bottom of the inner tank, the piping (14) for the circulating primary heat-transferring medium and the piping (9; 23) for the secondary heat transferring medium within the outer tank being arranged to allow heat energy to be exchanged between the primary and the secondary heat-transferring medium.



For the following storage concept with the incapsulated PCM material, heat pump, heat distribution unit, and steering, a so-called 'novelty search' had been carried out in order to obtain 'freedom to operate'. We have found that we do not violate existing rights, and we have concluded that we do not wish to take out a patent for the latest iteration.

Energy policy objectives

Through the project, the heat pump system has been further optimized – becoming ideal for replacing oil and gas heaters. With the built-in heat storage, operation of the heat pump can be set at running outside the so-called "critical hours" where the electricity grid is at risk for being overloaded. The remote control is also an advantage for the operation of the electricity grid itself – hence making the system of interest to the energy companies with a more direct access to customers and grid-operators, as they may avoid investments in the grid to live up to higher electricity demands.

In this way, the project very directly supports Danish and EU energy policy objectives, supporting sustainable, green energy and lowering carbon dioxide emissions.

Sharing information

During the project, information about the project's TRNSYS model has been shared – in part – with the University of Aalborg.

In courses about energy storage at DTU, knowledge acquired through the project has been shared with students.

The families with test installations have been approached and accepted participating in further projects aiming at better steering.

1.7 Project conclusion and perspective

The project resulted in a well working heat pump with integrated storage that poses a well working alternative to fossil fuels in individual housing, supporting green energy solutions and Danish and international political climate goals.

Productionwise, the project has given a stronger foundation for a more mature and streamlined production and installation process.

Following the project, focus now also moves on to larger scale systems, both on larger buildings and, for instance, on gathering otherwise small scale, individual projects into systemized clusters of buildings. The future would then be on how to make these clusters work well together, also supporting sustainable energy solutions.

In co-operation with the energy companies and grid operators, the knowledge drawn from the project will ultimately support converting individual households from fossil fuels to heat pump solutions with an unmatched flexibility offering. Also, the tools for simulating larger buildings open the possibilities to make larger building part of the green transition, ensuring that larger buildings or building clusters can be managed. The simulation component can support managing excess power in the grid and grid operators become important co-operators.

Annex

ELEC-TO-HEAT. Analysis of new redesigned unit – Storage. WP5. By DTU.

ELEC-TO-HEAT. Teoretisk undersøgelse af varmepumpe. WP4. By DTI.

ELEC-TO-HEAT. Simulation model. WP 2-6. By DTU.

ELEC-TO-HEAT. MPE-vekslere i PCM buffer. WP 1. By DTI.
(Note about MPE channels in the PCM buffer.)

ELEC-TO-HEAT. Krav til isolering af nedgravet lagerbeholder. WP 1. By DTI.
(Note about Insolation of a tank inserted in the ground.)

ELEC-TO-HEAT. Laboratorieforsøg med luft til vand-varmepumpe med propan som kølemiddel. WP 4. By DTI.
(Lab test of an air-to-water heat pump with propane as refrigerant.)

ELEC-TO-HEAT. Analysis of data from field test of re-designed systems. WP8. By DTU.

ELEC-TO-HEAT. Udnyttelse af varmelager og variable el-tariffer. By Suntherm.

ELEC-to-HEAT. Artikel: El til varme på en ny måde. By Ivan Katic, Rasmus Borup, and Claus Schøn Poulsen, DTI.