Executive summary:

Strategic overall objective

The overall objective of PIPESTORE is to develop a modular phase change material thermal store that enables optimal use of reneweable energy systems. Although the concept of phase change thermal stores is not new, the PIPESTORE project discriminates iteself by deliberately operating in super-cooled mode. The advantage of this is that long term storage of latent heat is enabled, greatly reducing standing losses, and enabling better optimised supply / demand management of the intermittent renewable energy source. For example solar energy is only available in daylight hours, but the demand for space heating and hot water peaks in the evening.

Generally super-cooling has been regarded as a problem for salt-hydrate based phase change materials, however by gaining control over the process it can be turned to advantage. In this respect sodium acetate has extremely interesting properties including relatively high specific latent heat of melting/solidification, relatively high thermal conductivity (for a phase change material compared with paraffins) and most importantly its propensity to super-cool up to approximately 80 K below its normal solidification temperature.

Operation in super-cooled mode however requires several elements to operate effectively:
a) Design of store with sufficient heat exchange area to attain reasonable charge/discharge times whilst maintaining a high volume fraction of the active phase change material
b) Good control over the time-temperature history of the phase change store in order to reliably attain the super-cooled state. This requires state of charge sensors (phase and temperature)
c) A means of initiating nucleation of the super-cooled sodium acetate which can be controlled electronically
d) A control system with software eneabling the end user to setup the release of stored energy in response to demand
Thus the project focused on these requirements.

Market drivers and potential

Despite current economic conditions the market for renewable heating technology is expected to continue growing. Optimal use of intermittent solar energy requires a large thermal store, up to 1000 l for domestic installations, however few dwellings have either the space or even required floor strength to accomodate such stores. PIPESTORE addresses this problem by increasing the energy density (compared with a hydronic sensible enthalpy store) by utilizing latent heat. Furthermore the PIPESTORE solution is modular and therefore highly scalable as well as straightforward to install.

Additional spillover applications for components of the technology developed in PIPESTORE include the replacement of inefficient and difficult to control electrical storage heaters. In this application the storage of thermal energy for indefinite periods can help to balance loads on the electrical grid, which is especially important due to increasing penetration of intermittent renewable electricity sources (such as wind turbines). The second application is the recovery of waste heat from industrial process.

Project Context and Objectives:

1. Concept and project objective(s)

Domestic heating and hot water preparation accounts for close to 40% of the overall EU energy consumption, and is still largely dependent on fossil fuels. Over the last decade, rising energy prices, concerns about global warming and the security of EU energy supply have led to increasing interest in domestic scale Renewable Energy Systems (RES). These include solar thermal, heat pumps and biomass technologies. This growth is likely to accelerate further in light of the implementation of the Renewable Energy Directive which will require Member States to develop their own action plans. In some cases this may lead to mandated integration of RES within new buildings (ie German RES law).

However despite these positive growth rates, the proportion of renewable energy used for domestic heating and hot water preparation is still well under 1%. Moreover, rapid growth has often come on the back of government incentives and subsidies which are temporary and unreliable. An example is the German market which experienced a 58% growth rate in 2006 before declining by 33% in 2007 when local VAT rates changed. However, besides the huge differences in local government incentives there are several more fundamental barriers to RES market penetration:

i) High equipment and installation cost of RES can lead to long payback periods and low return on investment. Integration of a solar thermal system often necessitates the installation of a compatible hot water store which adds significant cost. Moreover, in many households there is insufficient space for large, bulky water storage containers.
ii) The number of different types of RES is continually increasing. As opposed to the market for conventional heating systems, the market for RES is highly fragmented with thousands of SME participants. The resulting diversity and lack of clear standards makes it difficult for consumers to choose an appropriate technology for their specific situation.
iii) System diversity increases the complexity for installers. This often leads to suboptimal RES integration and operation which will prevent optimal use.

1.1 Conventional hot water storage and RES

Thermal storage is an essential part of most RES. Without an adequate thermal buffer, performance is significantly reduced. As a result, solar thermal collector area is directly proportional to available storage. Thermal storage also affects the performance of heat pump systems. The performance of a heat pump system is dependent on the temperature difference between the heat source and heat sink. Hence, its Coefficient of Performance (COP) will decrease when heating is most needed. Pairing these types of RES to a sizeable thermal energy store is therefore important in order to overcome the mismatch between renewable energy availability and domestic thermal energy consumption. However, due to space limitations and standing losses it is often not feasible to install larger water based thermal stores. In addition, modern high energy efficiency combi-boilers do not require a water storage tank. As a result it is unusual that a RES is considered, as this would require the installation of a new large thermal storage tank, in what are often smaller properties.

1.2 Emerging thermal storage technologies

There are two main alternatives to a sensible heat store (water based store) namely: phase change materials (PCM) and thermo-chemical materials (TCM). TCMs possess a very high energy density and rely on a reversible chemical reaction (hydration and dehydration of salt hydrates) to provide nearly loss-free long-term storage. Their main limitation is effectively managing the hydration and dehydration process which is currently not economically feasible in a domestic setting. PCM's have a lower energy density of 2 to 4 compared to water and are freely available at relatively low cost. However, the main drawback of PCM's is that they generally have a very low thermal conductivity and also a low sensible heat capacity. This means that they will only provide a benefit compared to sensible heat stores when they are operated over a narrow temperature range, typically around the phase change temperature. The conventional design of domestic heating and hot water systems relies on sensible heat storage which is a direct function of temperature difference. This means that the usable and accessible energy contained within the store at any one time is dependent on the temperature drop allowable until the boiler fires. This type of system control is perfectly adequate for use with sensible heat stores but usually prevents effective usage of latent heat storage. In addition, techniques to improve heat transfer rates (ie encapsulation) often lead to significantly reduced energy density, thereby decreasing the inherent benefits when compared to water. As a result, despite a substantial knowledge base there currently exists no cost-effective, flexible PCM based storage solution suitable for integration in a domestic heating and hot water configuration.

1.3 Commercial Opportunity

Our consortium is led by New Wave Innovation and along with Solimpeks who is one of Europe's leading flat pate solar collector manufacturers and Saturn Engineering, we have identified a huge commercial opportunity for new thermal storage technology which overcomes the existing PCM storage limitations. This should be a low cost modular design which can be scaled according to the application and does not require a large single volume of space. A modular design will benefit from economies of scale, enabling the technology to be mass produced in order to reduce the retail price. In addition, a distributed store will also increase the installation flexibility, with the ability to combine multiple energy sources.

There are currently no technologies which can fulfil this market gap. As a consortium, we are ideally placed to exploit this opportunity. However, this can only be achieved by overcoming several technical barriers. This will enable us to expand our businesses and internationally, export our European owned technology.

1.4 The PIPESTORE Concept

The aim of the PIPESTORE project is to develop a flexible, cost effective high density thermal store that enables effective use of conventional RES, such as solar thermal and heat pump systems. The PIPESTORE concept is based on the development of a modular 'pipes-in-a-pipe' low-cost thermal store, utilizing supersaturated solutions of sodium acetate (CH3COONa). Sodium acetate is able to supercool far under its phase change temperature (under the right conditions). This enables long term loss-free storage. Sodium acetate is an inexpensive and non-toxic chemical, produced in industrial quantities for wider range of applications including food flavorings, hand warmers and heating pads. Unlike state-of-the-art thermal storage technologies utilising supercooled PCM will enable us to charge and discharge thermal energy rapidly on demand by nucleating the solidification process.

In order to overcome the low thermal conductivity of sodium acetate a 'pipe in pipe in pipe' design will be used to optimize the conflicting requirements of sufficient heat exchange area and volume fraction of active material. Overall, PIPESTORE will achieve an energy density of at least 2 compared to water based stores and will virtually eliminate standing losses. This will be very attractive to end-users and will help reduce the payback for most RES.

PIPESTORE will also include a control system and user interface which will provide feedback on the system's capacity and enable effective actuation control, through an innovative nucleation trigger. Multiple modular stores can be distributed throughout a domestic or commercial building with a solar, ground or air source heat pump. Pipes may be installed in series or parallel according to the application.

1.5 Scientific and Technical Barriers

However, in order for us to commercialise the technology we must overcome some significant scientific and technical barriers. In particular we must research into and characterise the supercooling of PCMs in relation to the proposed PIPESTORE configuration, in order to understand their performance characteristics during charging and discharging. We will also need to perform thermofluid modeling, to design and optimise the PIPESTORE geometry. Furthermore, research into and development of a low cost actuation and control technology must be undertaken. This will be followed by system modelling of PIPESTORE, as part of a range of domestic heating, hot water and renewable energy systems.

1.6 Potential impact

The main benefits of PIPESTORE are its flexibility and low cost. Compared to conventional twin-coil hot water cylinders which often cost greater than 1,000 EUROS (ex installation) PIPESTORE can be scaled and customised cost-efficiently to suit any RES and any property. The system can be positioned in a loft, between walls, in a garage etc. This means that dwellings with space limitations can also benefit from RES. Although similar concepts have been proposed in the past, they have never been successfully developed and commercialised. The market for thermal storage relating to RES is currently 500 million EUROS in the EU and is expected to expand at a rate of at least 10% per annum. Our aim is to capture a 5% market share by 2020 which will be worth between 30-40 million EUROS per annum.

1.7 Objectives

Scientific objectives
1. Characterisation of super-cooling and nucleation phenomena of candidate PCMs for use for PIPESTORE
Success criteria: Expermentally validated data which can be used to predict the degree of super-cooling achievable under controlled conditions
2. Thermofluid model to determine energy transfer from the PCM to the heat transfer fluid during charge and discharge cycles as a function of store and heat exchanger geometry
Success criteria: Determine the optimum combination of heat transfer surface, co-axial pipe geometry and flow rates (5-30 litres per minute) as a function of PCM type and supercooling/ nucleation characteristics
3. TRNSYS modelling of conceptual PIPESTORE system as part of a range of conventional and emerging domestic heating, hot water configurations and renewable energy systems
Success criteria: Determine flow rates for charging and discharging to match performance of existing RES and match demand of typical households. Validate performance of conceptual topology as a function of heating and hot water system infrastructure.

Technical objectives
4. Design of overall PIPESTORE geometry and insulation to achieve optimal compromise between energy density and heat transfer rate
Success criteria: Achieve an overall energy density by volume of at least 2.5 times that of conventional sensible heat stores
5. Development of a actuator to initiate discharge of supercooled PCM
Success criteria: A low-cost, reusable and durable (greater than15 years) shape memory alloy actuator
6. Development of a control algorithm to optimise the use of the PCM store as a function of usage profile and RES/ heating system topology
Success criteria: A low-cost wireless control system that maximises the yield of RES and is capable of satisfying hot water and/or heating demand
7. Develop flexible topology for effective integration into a range of domestic heating and hot water configurations

Success criteria: Methodology for cost-effective integration of PIPESTORE within at least 50% of conventional European heating and hot water configurations

Integrated objectives
8. Prototype of integrated modular PIPESTORE PCM storage system

Success criteria: Achieve an overall energy density of at least 2.5 time that of water, a minimum of 8,000 full charge/discharge cycles and a sales price of 700 EUROS for a 50kg system consisting of 10 modules

9. Validate improved payback and increased RES yield through integration of PIPESTORE

Success criteria: Demonstrate a reduction in total solar thermal system integration cost of 30%, a potential seasonal performance improvement of at least 20%.

Project Results:

The main results generated by the project were as follows:

1. Phase change material characterization and topology integration
2. Thermofluid simulation and mechanical design
3. Nucleation actuator
4. Digital hardware and firmware design
5. Working thermal store prototype and trial results

Result 1

Phase change material characterization

The main criteria to select a PCM for a practical application is its phase change temperature (melting point). However, they are other important parameters that must be taken into account such as: latent temperature, stability to cycling, and thermal conductivity 1, 2.

Common demands on PCM are large amounts of latent heat and high thermal conductivity. They should also have an eligible melting temperature in a practical range, melt congruently with usually minimal supercooling and be chemically stable, low in cost, nontoxic and noncorrosive.

Materials proposed as PCM after forty years of study are hydrated salts, paraffin waxes, fatty acids and eutectics of organic and nonorganic compounds. The most auspicious PCMs are salt hydrates and paraffin waxes.

Commercial paraffin waxes are cheap with moderate thermal storage densities and have a wide range of melting temperatures. They melt without phase segregation, are chemically stable and undergo negligible supercooling. The low thermal conductivity (~0,2 W/mK) however limits their applications.

Hydrated salts are attractive materials due to their large amount of latent heat, relatively high thermal conductivity (~0,5 W/mK) and low cost. Phase segregation, supercooling, corrosivity, lower density compared to paraffin waxes and instability on cycling are major problems related to salt hydrates. The large amount of latent heat, high thermal conductivity and supercooling abilities made the use of salt hydrate in this study attractive.

The main goal of this study was to select the most adequate PCM for thermal energy storage that would enable the optimal performance of renewable energy system.

On the base of conducted literature research, the three PCM of different chemical and thermal characteristic have been selected: sodium acetate trihydrate (SAT), and two commercially available PCM materials: Plus ICE A58 - paraffin based PCM); and Plus ICE S58 – PCM based on eutectic salt $Mg(NO_3)_2/MgCl_2 \cdot 6H_2O$. In order to determined they thermodynamic properties, selected PCM were subjected to thermal characterization by application of techniques of thermal analysis: thermo gravimetric analysis (TGA), and differential scanning calorimetry (DSC). Furthermore, in order to follow melting properties of selected PCM, depending on chemical composition of PCM, sample holder type (material type, geometry) it was carried out some thermal measurements in thermal chamber.

Obtained results confirmed that SAT is the most adequate PCM for using in thermal storage, and give as some useful information for further progress of the project (such as solving task connected to thermofluid modelling, PIPESTORE design).

Results of DSC measurements carried out with different cooling rate (2-15 °C/min) have shown that cooling rate of liquid SAT, has significant influence to temperature of crystallization, and consequently to degree of supercooling. Namely, SAT sample cooled by lower cooling rate will have lower values of degree of supercooling (for cooling rate 2 °C/min degree of super cooling is 41.14 °C, while cooling rate of 10 °C/min will resulted with degree of supercooling of 75.08 °C).

Results of thermodynamic characterization of PCM obtained by heating in thermal chamber didn't show any significant difference between melting properties of all three selected PCM. Generally, testing has shown relatively low value of melting rate for all tested PCM, while in the case of SAT was present precipitation of no-melted SAT on the bottom of the sample holder.

In the case of planed configuration of PCM storage pipes (horizontal placement and low diameter), it can be assumed that problem with precipitation of no melted SAT wouldn't be so pronounced.

On the other hand, relatively low value of melting rate was dominantly influenced by low value of thermal conductivity of sample holder (glass, plastic), that was chose only for purpose of experiment (from practical reason). Namely, for purpose of experiment it was necessary to chose transparent sample holder in order to enable following of melting progress. In the case of real solar system, PCM will be placed in pipes made from the material with ten to hundred times higher values of thermal conductivity (such as cupper, aluminium, or stainless still, Tab.21 (in Appending 7)), so considering to that it can be assumed that melting rate in real system will be much higher. Likewise it is also possible to increase relatively low value of thermal conductivity of PCM, by adding some amount graphite particles, since graphite has high values of thermal conductivity, Tab.21. Next step in that direction will be experimenting with mixture of SAT and graphite, where graphite would be mixed in powder form with SAT in various ratios. Results will be then compared with results obtained from test on SAT without graphite.

Results has also shown that during the preparation of the material/melting (heating at the temperature above water evaporation) is necessary to prevent loss of the water; accordingly content of the water has height influence to melting rate of SAT (by decreasing of the water content, decrease the melting rate).

Except, chemical composition of PCM material and sample holder material type, the melting rate are also influenced by some dimensional and thermodynamic parameters of investigated solar system, like diameter of PCM holder pipes (smaller diameter will increase heating rat), and temperature and flow rate of fluid which is located around the PCM holder pipes. It is important to model optimal PCM holder geometry to with the aim of obtaining best possible heat transfer between PCM and the fluid (water). According to this, simulations of various geometry configurations and different materials of PCM holder will be conducted.

For optimal performance of renewable energy solar system it is important to select the material for PCM sample holder that has high value of thermal conductivity, to choose appropriate configuration and dimension of the PCM holder pipes system, and to define the most appropriate flow rate of the fluid placed around the PCM holder pipes.

Topology integration

The aim of PIPESTORE is to integrate with as many existing domestic heating and/or hot water topologies as possible. In reality the consortium will have to focus on 1-2 topologies that are most relevant.

The theoretical energy stored within a typical hot water store is calculated by:

Q = mass X Delta T X specific heat capacity of water (4.2kJ/kgK)

However, in reality the usable energy contained within such as store is much smaller than the theoretical energy contained and is defined by the usable temperature range. This is the difference between the average store water temperature and the boiler firing or solar thermal system triggering point. This delta temperature is usually no more than 20-30°C. In a typical 200 litre store this means that a maximum usable energy of 4.6-7kWh is available at around 60°C. This is usually sufficient for 2-3 average showers.

The benefit of using a sensible heat store is the linear energy storage capability and relatively rapid energy release (thermal power available). The drawback is that unless the store is significantly stratified it can only be charged once there is a temperature differential between the store average (i.e. 60°C) and the energy source. In solar thermal systems this is usually greater than3°C, which triggers the systems pump. Actual operation depends on whether a passive i.e. natural convection (thermosiphon) or active (pumped) systems is used.

Solar thermal systems are less efficient if the temperature differential with the ambient is large. Hence, ideally they need to operate at temperatures below 70°C. Another consideration is that large water stores will have significant standing losses unless significant insulation is provided, which adds to the space requirement for the store.

Potential PIPESTORE configurations and topologies

In order for PIPESTORE to be relevant it must be able to interface with and integrate within existing domestic heating and hot water topologies. For commercial purposes it is of course essential that PIPESTORE can be integrated with most existing systems. However, for research and testing purposes as well as demonstration purposes we must select the most relevant and promising configurations, where PIPESTORE brings most benefits. The following topologies are mainly based on Northern/Central Europe.

These will be a) combi (flow) boiler scenarios and b) water storage based systems. It must be noted that PIPESTORE will not be intended to completely eliminate the need for a sensible (water based) store. Based on the consortiums research and outcome of D1.1 it became clear that the most benefits could be derived by i) storing of additional energy at higher energy density and virtually loss free (supercooling); ii) storing energy at lower temperatures 30-55°C in order to capture lower grade solar energy when limited solar irradiance is available. The latter could increase the systems seasonal performance, but can only be achieved by non-supercooling PCMs. Both these concepts can be integrated as a pre-heat function, to heat cold mains water before it gets to a boiler or water store OR by directly supplying hot water from the PIPESTORE elements.

PIPESTORE topologies specification

Following extensive research and discussions between the consortium members including input from Mr Dale Courtman (NWI) who in a previous position was Technical Director of the UK Chartered Institute of Plumbing & Heating Engineering (CIPHE), it was decided that for the purpose of the project and to validate the performance of PIPESTORE, two topologies should be selected for the initial specification. These will be modelled as well as tested in the PIPESTORE solar test rig. The combi-boiler topology will be important for the purpose of commercialisation but it was decided that a solution can relatively easily be developed once the concept was proven with a system based on a water store.

It was decided to verify the performance of both a parallel and a series configuration. This approach would also help to verify and understand the effect of close coupling the PIPESTORE modules to a solar panel.

Conclusions

Following research by the partners as well as detailed discussions during PIPESTORE meetings in Zagreb and Munich, the consortium decided to focus on two topology configuration which will be modelled and testing using the PIPESTORE test rig. The control system development will also be based on these configurations which will be in series and in parallel topologies. Novamina will undertake the modelling work and thermodynamic testing on a single PIPESTORE module on a dedicated lab test rig, whereas New Wave Innovation and Biodigital will perform the testing mainly in relation to the PIPESTORE actuation and the control system on the PIPESTORE test rig which is currently situated with New Wave Innovation in the UK.

2. Thermofluid simulation and mechanical design

Thermofluid simulation

The modelling was done applying one-dimensional model of heat transfer in cylindrical PCM stores geometries, and self-made computer program named PIPESTORE. The program is based one-dimensional model described in Deliverable report 1.2, and numerical solution of the energy balance equation applying finite difference numerical technique described in D2.1 report Section 2.3.

The main characteristics of PIPESTORE code are:

- It is applicable for cylindrical geometries of PCM thermal stores
- It takes flow characteristics of heat transfer fluid to calculate heat transfer coefficient in the case of forced convection (from Prandtl nuber , Reynolds number, and Nusselt number)
- It models phase changes applying the effective heat capacity model
- Heat transfer from pipe to PCM during melting process is modelled assuming heat conduction mode only at the beginning when PCM is solid, and then by natural convection when PCM begins to melt in vicinity of the pipe surface. Heat transfer coefficient in the case of natural convection is calculated from Nusselt number (which is calculated from Grashof, Rayleigh, and Prandtl numbers)

- Heat transfer between PCM and pipe during solidification process is modelled using heat conduction mode
- The program enables calculation of temperature vs. time profiles at different locations along PCM and pipe, as well as to derive many important information necessary to characterise thermal behaviour of a given PIPESTOREs system configuration.

The PIPESTORE computer program is useful toll in thermo-fluid modelling, particularly for studying effects of various parameters on performance of particular PIPESTORE system.

The program is validated by comparing calculation results with the results of ANSYS code, but it should be further validated comparing calculation results with experimental results which should be obtained on real PIPESTORE configuration using a test rig.

On the basis of numerous calculations we made and the results presented in the study, the following conclusion regarding the effects of individual parameters on PIPESTORE performance, and possibilities to enhance performance of PIPESTORE, can be drawn:

Possible geometrical design of PIPESTORE design

On the basis of the results of numerical modelling, as well as available literature information on various aspects of LHTS systems, particularly enhancement techniques, we came to the following conclusions:

a) Enhancement of thermal conductivity of SAT seems to be efficient way to enhance charging/discharging characteristic of PIPESTORE system, however at this stage we cannot rely solely on this enhancement techniques due to fact that we are not sure that an appropriate graphitised SAT is easily commercially available (?)
b) Assuming that low thermal conductivity of PCM will remain limiting parameter, another possible approach is to decrease thickness of PCM layer in order to reduce effect of low thermal conductivity, and to increase heat transfer surface at the same time. Possible design, which is based on modification of original conceptual design, and consist of hollow cylinder filled with PCM (so-called "pipe-in-pipe" configuration).
c) Table 6.1 gives summarised results for original design ("full pipe"), and two possible (candidates) configurations; one if based on "pipe-in-pipe" design, another uses enhancement of thermal conductivity of PCM to enhance heat transfer characteristics of PIPESTORE system.
d) As shown from Table 6.1 in deliverable report 2.1, by using "pipe-in-pipe" configuration charging/discharging times are much shorter than by using original conceptual design ("full pipe"), and thermal power is much higher . Along with acceptable charging and discharging times, this configuration has higher energy density
Assuming we will use standard SAT, with low thermal conductivity, it seems from data given in Deliverable report D2.1 Table 6.1 that "pipe-in-pipe" configuration may be a "promising" solution.
Further experimental study will be required to optimise dimensions of pipes in accordance with specific requirements (e.g. given maximum volume, certain value of melting time, thermal power, storage capacity, etc.).

PIPESTORE MODEL

Introduction

Idea was to simulate PCM storage impact on the energy balance of the typical solar system through winter and summer period. Model consists of three key components, solar flat plate collector, solar storage tank and PIPESTORE module (PCM heat storage unit). System was modeled as a typical solar thermal system for domestic hot water on a family house, located in Zagreb-Croatia but with addition of Pipestrore PCM heat storage. Characteristics of solar collector were taken from Solimpeks Wunder CLS 1808 flat plate collector. During initial analysis it was noticed that PCM unit will have greatest impact on a system with smaller water storage so smaller than typical for this system water storage tank was chosen as a part of the model. PCM storage tank was modeled using PIPESTORE code software described in deliverable D.1.2 Thermo fluid modeling for "pipe in pipe in pipe" tank configuration. Simulations were conducted for winter and summer period with an emphasis on energy stored in water storage tank and temperature inside water storage.

Dynamic simulation model described in this report was primarily designed to see the effect of a PCM type storage module (PIPESTORE unit) on the actual solar hot water system. As already mentioned key difference between usual solar system and the one that was analyzed is in the water storage volume. By choosing relatively small water storage (80l) we have increased the positive effect of a PIPESTORE unit on system efficiency because with a bigger storage tanks (150-200l) PIPESTORE unit, which has a smaller storage capacity than a larger water tank, does not have significant affect on energy efficiency during discharging (in this case this is partly because our PIPESTORE unit is relatively small with about 30kg of PCM).By analyzing results for summer and winter period it is clear that PIPESTORE shows its efficiency during discharging in evening peak periods. Future analysis should be taken into consideration combining two similar PIPESTORE units with which would then be discharged in both morning and evening peak period. Also different sizes of storage module and combination of modules with different PCM-s should be considered. PCM-s with different melting temperature would give more flexibility to the system because with Sodium Acetate which has a melting temperature of 58°C, HTF (heat transfer fluid) temperatures significantly above 60°C are needed to melt PCM in a relatively short time period. Altogether PIPESTORE type storage unit shows some positive effect and potential as solar thermal energy storage but it also requires further analysis and optimization regarding storage size, solar system type and PIPESTORE unit integration.

Mechanical design

Introduction

Main goal in this part of the project was to develop design concept for the prototype of PCM heat exchanger. All kinds of different geometries and materials were taken into consideration but in the end basic pipe in pipe configuration with aluminium or stainless steel (because of their good thermal properties) were chosen as optimal solution. Initial prototype solution was devolved from the results of thermo fluid modelling. Basic goal was to decrease PCM melting time on the one hand but with sufficient amount of PCM in other words, stored energy/latent heat. Another issue that was taken into consideration was integration into existing hot water home applications. In following chapters, design development, material selection, manufacturing and testing of PCM heat exchanger will be described.

Idea was that the SAT (sodium acetate trihydrate) is placed inside the middle pipe and water is circulated through outer and inner pipe, in that way heat transfer goes in two directions during the crystallization and melting which during simulations and modelling proved to be efficient. Left plug was used as a piston on one end of PCM tube an it served for pressure release due to volume increase during the phase changes.

Prototype design

Initial tests with the 'pipe in pipe' heat exchanger had shown that considerable practical difficulties existed in terms of both sealing the unit, and the manifold required for the heat exchange fluid. Although all of these difficulties could have been resolved by further development a decision was taken to proceed with a simpler solution based on integrating the PIPESTORE module directly inside a thermo-syphon tank of a solar system. This would mean that natural convection rather than forced convection would be relied upon for heat transfer at the outer radius, however forced convection would still be employed for the axial pipe.

Based on the experience from initial prototype development it was decided as mentioned before to develop more simpler and efficient solution. Application chosen for prototype integration was SOLIMPEX TSM 200 Thermosiphon system.

Conclusion

After choosing initial Pipe store module concept, several redesigns were necessary to get final acceptable solution. Basic concept was kept during all the changes (pipe in pipe).In pre prototype stage, after unsuccessful testing, materials selection and process monitoring were identified as main flaws. That served as a basis for prototype design which was devolved for integration into TSM 200 thermo siphon tank. After prototype module completion and subsequent testing two main flaws were noticed, sealing and possibility of tank integration. All of the mention issues were resolved in final module design which has been pressure tested without leakages and on which super cooling effect was proven. Final module design is compact heat exchanger based on the pipe in pipe concept that combines excellent sealing, thermodynamic properties, cost effectivnes and possibility of integration on the thermo siphon tank or if necessary other water storage tank types. Details are described in Deliverable report 2.2.

3. Nucleation Actuator

The objective was to develop a nucleation initiation device that could be easily interfaced to the control system to be developed by BioDigital. Initially it was planned to use a shape memory alloy actuator in a manner which was directly analogous to the metallic triggers used in commercial heater pads. These triggers depend on the preservation of small amounts of solid sodium acetate even during the charging (heating) phase due to the presence of cracks within the metal. These cracks are formed by stamping indentations and partially flattening the indentations. It was realized that this would be a problematic to reproduce with a shape memory alloy as they are particularly difficult to cold-form. Also when examined under a microscope it was found that a commercial trigger actually was cracked through the thickness of the material. These cracks were of a size that would almost guarantee failure via low cycle fatigue within the target lifetime of 15 years.

It was therefore decided to explore other means of initiating nucleation. In order to do this the theory of nucleation of sodium acetate was reviewed. The most probable reason for supercooling behavior of sodium acetate is the fact that formation of incipient nuclei of critical size has a maximum free energy of formation. Thus growth of clusters to the critical size is thermodynamically unfavourable, but once a critical size incipient nuclei is present it exhibits rapid growth because the free energy of formation of larger clusters is lower.

Methods of initiating nucleation were discussed including cooling below 250K, application of high pressure, crystal seeding and electro chemical methods. Cooling and high pressure were dismissed because of high energy requirements and impracticality. A literature survey indicated that electro chemical methods were potentially effective, therefore a co-axial copper, stainless steel electrode system was designed and manufactured. This was connected to a variable voltage laboratory power supply via a solid state relay that was triggered by a signal generator so that a wide range of waveforms, frequencies and voltages could be trialled.

Within the timescale available the electro chemical technique could not be made to work successfully even when replicating the conditions described in the literature. For this reason crystal seeding using a simple mechanical actuator was selected as the most reliable technique.

It became obvious that to work in a range of different store geometries, a variable stroke actuator would be required so a solution based on a stepper motor with a leadscrew was adopted. The leadscrew was equipped with a stainless steel rod that dipped into the liquid sodium acetate. This rod had features (holes or grooves) designed to retain solid sodium acetate. The idea was to withdraw the rod in to the body of the actuator during charging so that the solid sodium acetate would remain in these features. The first generation unit was successfully manufactured and tested by NewWaveInnovation. A second generation unit was also manufactured this time from ABS polymer in order to ease manufacture and reduce costs.

In the future the electro chemical approach is still appealing because there are no moving parts and possibility to greatly reduce costs.

4. Digital hardware and firmware design

The purpose of the control system is to enable optimum use of the phase change thermal store in super-cooled mode. Optimum use can be defined as the ability to store energy when demand is low, and then release it upon an increase in demand which cannot be fulfilled by input from the renewable source alone. At the same time practical requirements mean that the system should be easily installed in a wide range of different system topologies.

It was developed on the basis that it would need to be independent of the solar system topology. Discussions with consortium members revealed that the possible range of topologies is very wide indeed, and each of these topologies may have a different optimum location for the PIPESTORE modules. Attempting to develop a control system for all topologies would require extensive customization for each installation, making it virtually impossible to achieve.

Regardless of topology, if the PIPESTORE modules were close coupled to the solar panel, then they would absorb energy from the heat transfer fluid until they were fully charged. Release of this energy upon demand would then be an identical process to heating due to the panel. This philosophy means that the PIPESTORE control system can be decoupled from the solar control system and therefore becomes universally applicable to various topologies, with either no or mimimum changes.

The control system architecture consists of node boards for each PIPESTORE module. Each node board has two sensor inputs consisting of an optical reflectance state of charge sensor and a temperature sensor. The optical reflectance sensor detects the change in reflectivity of the sodium acetate when it changes phase. Reflectance is low in the liquid state, but increases almost stepwise when solidification occurs. The combination of temperature sensor and phase sensor enables the state of charge to be read. The node board also drives the nucleation initiation actuator, which at present is a stepper motor driver, however this can be easily adapted to new types of actuator. The nodes communicate with a central control system over a wired CAN bus.

The central controller communicates with a PC over a WiFi network. The software solution developed enables the end-user to programme the schedule of energy release from the PIPESTORE modules via an intuitive graphical user interface. The software also has an 'engineer' mode which gives access to the sensor inputs allowing the installer or technician to diagnose correct operation of the PIPESTORE units and sensors. Both the control system and the software solution have been developed to a standard that is very close to production prototypes. Only minimal additional effort would be required to commercialize these components.

The control system may be applied for a range of different purposes and not just PIPESTORE. Indeed phase change stores may be a good replacement for electrical storage heaters which are still in extensive use throughout Europe. The control system would be perfectly suitable for this application with little or no modification.

5. Working thermal store prototype and trial results

The prototype PIPESTORE modules consist of a stainless steel cylinder with an axial pipe. The volume of the cylinder allows a fill of 10 kg sodium acetate. It is anticipated that in a full scale installation several modules would be specified, depending on the area of the solar collector. The complete unit is designed to be integrated with a thermo-syphon solar tank. This simplifies the plumbing requirements greatly, and ensures that no additional space is required. The unit is equipped with ports that allow filling with sodium acetate as well as the integration of the actuator and state of charge sensors (consisting of an optical reflectance sensor and a Pt 100 temperature sensor).

Several design iterations were required to arrive at a final design which could be successfully integrated with a full scale solar system. Prevention of a sodium acetate leak was critical because this could cause serious damage to an expensive solar system due to corrosion, but more importantly there was also a remote chance that water supplies could be contaminated. The design was therefore modified to eliminate the seals where this possibility existed and the unit pressure tested to ensure that any potential source of leakage was eliminated.

Changes were also required because considerable difficulty was encountered in proving that super-cooling bulk quantities of sodium acetate could be carried out reliably. It was already known (from the work embodied in result 1) that the cooling rate of the sodium acetate was a key parameter governing the extent to which super-cooling below the normal solidification temperature would occur, however it was still not known if small scale laboratory experiments could be extrapolated to the full size unit.

In order to test the complete PIPESTORE system it was plumbed into the small solar rig that had been built by BioDigital to develop the control system. Because the cylinder of this unit was too small for the PIPESTORE unit to be installed within, the heat flux from the outside of the PIPESTORE unit was simulated by applying two 400 W heater pads. The axial pipe was connected to the rig, which together with the heater pads allowed good control over the time-temperature history of the sodium acetate.

We have now successfully and repeatedly demonstrated operation of the PIPESTORE thermal store in super-cooled mode. In the present configuration the temperature change of the water in the cylinder due to discharge of the PIPESTORE unit is not representative of the stored latent heat because most of the heat is radiated to the surrounding atmosphere. Thermal insulation was tried in a previous attempt, however this reduced the cooling rate to the extent that only minimal super-cooling was achieved. This issue can be overcome by integrating the module in the intended manner, however the modeling results (result 2) indicate that the potential benefit in a solar installation is modest, unless the thermal store is very small.

We now believe that a better application for the PIPESTORE technology is as a replacement for electrical storage heaters and for recovery of low grade waste energy from industrial processes. We are pursuing these ideas and NewWave Innovation has been awarded a phase 1 SBIR grant from the Department of Energy and Climate Change in the UK to continue what we have learnt in PIPESTORE.

Potential Impact:

The major benefits of PIPESTORE compared to conventional water based stores (in relation to RES integration) are:
i) improved energy density and thus smaller system footprint
ii) flexibility of installation (ie location);
iii) expandability;
iv) reduced initial investment cost of RES integration.

PIPESTORE can be scaled and customised cost-efficiently to suit any RES and any property and is thus relevant to a large proportion of European households.

The system can be positioned in a loft, between walls, in a garage etc. The following sections outline the market for RES and associated heat storage technologies in Europe, the market opportunity for the PIPESTORE consortium, benefits to the consumer, environmental benefits and the wider impact on Europe. This will be followed by a comprehensive Exploitation Plan, Dissemination Plan and Intellectual Property and Knowledge Management Strategy in Section 3.2 Market characteristics – heating and hot water systems in Europe

The European market for domestic residential scale heating and hot water related products is very diverse. This includes more traditional heating and hot water products such as boilers, hot water stores and fittings but also RES such as solar thermal, heat pumps and biomass boilers. Overall, it is estimated that this market is worth over 15 billion EUROS per annum in European alone. Approximately 70% of the overall market is dominated by large companies or groups such as BTT, Viessman, Vaillant, Baxi De Dietrich Remeha etc. The remaining 30% is split between several hundred companies many of which are SME's. As can be seen manufacturers either distribute via their own channels or via independent distributors or wholesalers.

The European market for domestic heating and hot water systems can be further split into: i) heating systems; ii) hot water systems; iii) RES compatible systems (ie solar, heat pumps, biomass). This is an increasingly awkward way of characterising the market as more and more technologies integrate the provision of hot water and heating. This includes the utilisation of thermal storage and RES which will be discussed in more detail in the following sections.

Classical space heating systems account for the large majority of sales, followed by water heating systems. Demand for RES as part of domestic hot water and space heating is increasing as part of new sales, but is still low in terms of installed capacity at just 8.5% of total energy demand. Of this the large majority is biomass leaving less than2% covered by existing solar thermal and heat pump installations. Overall, gas is the dominant energy carrier, followed by electricity, biomass and oil. However, it should be noted that the heating and hot water infrastructure varies considerably between different Member States and is a direct function of the type of energy carrier available and at what tariff. In some countries the gas network covers the large majority of homes whereas in others there is limited market penetration. It must also be noted that although gas may be available and used for domestic central heating, the energy carrier used for hot water preparation may still be electricity (ie electric hot water cylinders).

Renewable energy systems market – solar thermal and heat pump systems

In 2006 the global market for domestic scale RES (solar thermal systems, heat pumps, biomass boilers) was estimated to be worth over 3.5 billion EUROS. As opposed to the market for classical type heating and hot water technologies it is fragmented and dominated by a large number of innovative SME companies. As outlined in Section 1, solar thermal and heat pump system are likely to benefit most from effective thermal storage. The following analysis will therefore focus on the market development for these technologies. Solar thermal systems have been available for very long time. However, only recently has their market penetration started to increase significantly. Solar thermal energy is used for a wide range of applications including domestic heating and hot water, pool heating, drying and industrial heating. China has by far the largest market penetration of solar thermal systems as expressed in square meters and capacity (80.8GWth compared to 16GWth in Europe). On average Europe's installed capacity is growing rapidly but at times this growth has been volatile. For example, whereas the market expanded by 47% in 2006, it declined by 10% in 2007 before increasing by 60% in 2008. This is mainly the result of the large differences in market conditions within the European Union. For example, the main reason behind the 2007 decline was Germany's dramatic (temporary) decline in demand. Solar thermal capacity per capita (1000 inhabitants) varies enormously, ranging from over 800m2 in Cyprus, to Germany with over 300 m2 and countries such as Italy with under 100 m2. The overall European average is 54 m2. This is due to differences in heating infrastructure, tariffs, climate, GDP, available subsidies and government regulations/mandates. However, new progressive EC legislation such as the RES directive aim to reduce these difference whilst achieving ambitious market growth across the European Union.

The recently introduced Renewable Energy Directive aims to achieve an overall RES contribution of 20% of total energy demand by 2020. Heating and cooling is also covered which will drive further expansion of RES in this sector. Furthermore, as local Member State governments are keen to achieve their GHG reductions, it is expected that national initiatives such as mandates will be introduced over the next several years. Examples include the UK Code for Sustainable Homes and Germany's Renewable Heating/Energy Law which will stipulate the proportion of RES contribution to domestic energy consumption for new homes. In 2008, the overall market for solar thermal systems was estimated at 3 billion EUROS with the sector employing over 40,000 people.

Heat pump systems can be roughly divided into two major categories namely, air source heat pumps (ASHP) and ground source heating pumps (GSHP). Both work on similar principles, where an ASHP extracts energy from the ambient air and a GSHP energy from soil, rock or water. Both are considered RES as they can achieve a Coefficient of Performance (COP) of between 3-5 which means that for every unit of energy (usually electricity) input in kWh another say 3 units are extracted from the soil or air. Although the technology has been around for over 50 years market penetration has been limited until 2006 when growth was close to an average of 50% across the EU. In 2007, growth fell to a still respectable 6% before again accelerating to 47% in 2008 (570,000 units). According to the European Heat Pump Association (EHPA), initiatives such as the RES Directive have lead to a change in the market, where heat pumps are now an important alternative to conventional heating systems. However, as outlined previously market penetration is very much a function of the local infrastructure and electricity tariffs. It is important to highlight that the market penetration of ASHP systems is growing faster than that of GSHPs. Generally, speaking ASHPs are the more cost-effective alternative and an ever increasing number are used to provide both space and water heating. It is estimated that the market is worth 1.5 billion EUROS in the EU alone (as of 2008).

Market for domestic thermal storage products

In 2006 approximately 40 million hot water storage devices were sold globally. Over 10 million of these were installed in Europe. This market used to be mainly driven by new builds and replacement systems. However, since the advent of RES such as solar thermal systems the market has changed significantly. Hot water cylinders are now not only replaced when worn out, as installation of a solar thermal system will necessitate purchase of a compatible hot water store. As a result the potential market has expanded dramatically. Nearly all hot water cylinder manufacturers now offer twin-coil cylinders suitable for both solar thermal and heat pump systems. It is estimated that the total value of RES compatible storage is at least 0.5 billion EUROS and growing rapidly. This is over 15% of the total market for hot water storage in Europe. Products range from say 50 litres right up to 1,000 litres which are required for large area solar thermal combi-systems.

Major factors impacting on market demand

It is clear that the market for RES and associated products (ie thermal storage) is expanding rapidly. However, it is important to consider the main drivers affecting market demand. This will enable correct product positioning and therefore increase market penetration of PIPESTORE:

- Relevant local hot water and heating infrastructure varies considerably between different Member States. For example, in Germany solar thermal systems are popular as they integrate well with the country's predominant reliance on gas. However, in Sweden the large majority of heating systems are based on electric heating. Hence, heat pump technologies are more popular.
- A combination of subsidies, rebates and government legislation will drive market growth. As outlined previously, the German Renewable Heating law will require RES integration in new builds. In countries such as the Netherlands, subsidies make RES more affordable.
- Increasing popularity of combi-boilers which can deliver high flow rates on demand preclude the use of any RES as no hot water store is required.
- A large proportion of European homes are by definition excluded from covering a large proportion of RES to cover their heating and hot water demand due to space limitations which make it difficult to install hot water stores with volumes greater than200 litres.
- Climate is obviously a major factor in the choice of heating and hot water system. Solar thermal generally provide better yields in southern Europe.

Based on the market drivers outlined above, the consortium strongly believes that there is significant market potential for the PIPESTORE technology. There are close to 500 million citizens in the EU27 and over 200 million households. However, as outlined not all these households will be in a position to integrate RES. Furthermore, even if a household is interested in RES it may not be suitable to advice integration of PIPESTORE. In order to provide a realistic quantification of the market potential we have therefore made the following assumptions relating to RES:

- RES such as solar thermal and heat pump systems are most suitable for medium size family dwellings that currently use a hot water store and have sufficient roof space
- Solar thermal system are generally not suitable for homes with combi-boiler systems
- Multi-storey apartment blocks or flats can utilise RES but this is mainly as part of a district heating system which we will consider to fall outside the scope of typical domestic RES
- In 2008 greater than4.5 million m2 were installed in the EU27. This totals approximately 1.125 million systems if we assume an average system size of 4 m2
- In 2008 576,000 heat pump were sold in Europe of which 345,000 were ASHP
- Between 1-1.5 million hot water stores sold in the EU (2008) are RES compatible

Overall, we therefore conservatively estimate that these RES are suitable for at least 70 million dwellings. The following additional assumptions relate specifically to PIPESTORE
- PIPESTORE can be used in conjunction with both hot water storage based systems and combi-boiler set-ups which actually increases the potential market for RES
- PIPESTORE is most suited to small-medium sized RES where space constraints are a major consideration. This covers systems covering hot water demand and medium scale combi-systems (hot water and space heating). For large combi-systems of over 25m2 (space allowing) hot water storage cylinders will be most suitable (ie greater than1000 litres)
- PIPESTORE can also enable integration of RES in smaller dwellings and apartments where space is at a premium.

Overall, we therefore estimate that the market for RES in combination with PIPESTORE will be larger at 80 million dwellings. Hence, PIPESTORE will actually increase the potential market for RES integration.

Market Opportunity

Based on the key market drivers and assumption we have quantified the market opportunity as follows (initial average sales price of 700 EUROS ex. VAT which will increase at rate of 2.0% pa):

Year	Total RES Sales (units)	Total storage product sales (units)	Sales target (units)	Total sales (EUROS)
2012	2,116,800	1,500,000	0	0
2013	2,434,320	1,725,000	500	357,000
2014	2,799,468	1,983,750	1,500	1,092,420
2015	3,219,388	2,281,313	5,000	3,714,228
2016	3,702,296	2,623,509	15,000	11,365,538
2017	4,257,641	3,017,036	27,500	21,253,555
2018	4,896,287	3,469,591	45,000	35,474,116
2019	5,630,730	3,990,030	60,000	48,244,798
2020	6,475,340	4,588,534	82,500	67,663,329
	33,415,470	23,678,763	237,000	189,164,985

As can be seen, initially we will seek to gradually increase sales whilst we generate publicity and case studies which will enhance product awareness. This period will also serve to set up manufacturing and create economies of scale.

We have calculated an average profit component of 25% across the supply chain over the first 8 years of exploitation. However, in the first 3 years profits will be limited to approximately 10% per unit due to lack of economies of scale.

Based on sales of 185.8 million EUROS to 2020 we anticipate profits of approximately 47.3 million EUROS.

3.1.7 Impact on the consortium

Based on our key innovations the consortium has undertaken a preliminary cost-benefit analysis to determine the cost of production of the PIPESTORE system. It is obvious that cost of goods sold (COGS) will be very dependent on economies of scale. Overall, the consortium wants to provide a very significant saving to the consumer in terms of initial investment. We have therefore set an ambitious sales price of 700 EUROS per unit ex. VAT for a 50kg system consisting of 10 individual co-axial PIPESTORE elements. Despite this price we anticipate a profit margin of 10% during the start up phase when economies of scale are limited (see table) with margins increasing to 25% when production increases and the full benefits of economies of scale are achieved.

Initially we will offer a 95 profit margin to RES manufacturers/installers selling PIPESTORE which will increase to 180 EUROS by year 4 of exploitation. The manufacturing part of the supply will see total profit margins increase from 55 EUROS per unit initially to 104 EUROS. Please note that these figures exclude installation costs.

3.1.8 Benefits to consumers

In order for us to achieve the projected market penetration we must demonstrate clear benefits to the end-user. The most important benefit will be a cost saving compared to conventional sensible heat stores. As outlined the integration of an RES will usually require the installation of a compatible hot water cylinder. On average this adds 1,000 EUROS to the cost of a system, thereby increasing the payback period by close to 10 years. Based on our costings outlined previously we will demonstrate the financial benefits of PIPESTORE in the following scenarios:

	Sensible heat store	PIPESTORE
Size	200 litres (cylinder)	50 litres (10 modular units)
Effective energy storage	4.7 kWh *	4.7 + 3.8 = 8.5kWh
Cost	1,000 EUROS (ex installation)	700 EUROS (ex. Installation)
Installation	250 EUROS	300 EUROS
TOTAL integration cost	1,250 EUROS	1,000 EUROS

PIPESTORE can replace a conventional store (if such a store is present) OR add to it as is illustrated by the calculation. Here we add 3.8kWh of capacity to a system of 4.7kWh, thus in effect significant increasing the available thermal storage. However, this depends on the type of heating and hot water system topology.

Solar thermal scenario – a typical solar thermal system of 3m2 aperture area with a solar yield of 500kWh/m2 will provide a contribution of around 1,500kWh. If it were possible to utilise lower temperature solar energy (ie during winter, autumn, spring) then the solar yield can be increased to over 700kWh/ m2. This is difficult with a typical hot water store as its average operating temperature will be around 65°C. However, as PIPESTORE will consist of a range of PCM types with different melting temperatures it will be possible to capture lower grade solar heat as for example 40°C. We therefore believe that PIPESTORE will enable an effective yield of 600kWh thereby significantly increasing return on investment.

Comparison with solar thermal system of 3m2	Sensible heat store	PIPESTORE
Solar system cost (installed)	2,000 EUROS	2,000 EUROS
Hot water store (installed)	1,250 EUROS	1,000 EUROS
Effective energy yield/usage	1,500kWh	1,800 EUROS per kWh
Annual financial saving	135 EUROS	162 EUROS
Payback period solar thermal system	12	9
Payback period solar thermal system including thermal storage	17	14

As a result PIPESTORE will enable a payback of 9 years which is a 25% reduction compared to conventional hot water stores. A further significant benefit is that PIPESTORE is modular and can therefore easily be expanded should the solar collector be increased in the future. This is not possible with a conventional store which will have to replaced.
Heat pump (ASHP) – a heat pump can be scaled to provide 100% of hot water and heating demand. In case an ASHP is used an average seasonal COP of around 3 is feasible. Throughout the year, however, the COP will vary considerably as a function of the ambient temperature and the demand for heating (ie delta temp.). The smaller the temperature difference the better the COP will be. However, it is often difficult to maximise the COP unless a suitable buffer store is available. This is often the case in air-to-water systems. Using a buffer can theoretically increase the COP if the heat pump is used during the day and not when it is colder during night-time (this will also depend on available electricity tarrifs.). Overall, PIPESTORE will provide a similar cost saving compared in terms of integration compared to solar thermal systems outlined above (ie 25%). Moreover, if PIPESTORE enables larger thermal storage a wider range of temperatures then it is likely that a COP increase of 10-15% is possible which would result in savings of greater than 150 EUROS per annum on average.

3.1.9 Environmental benefits

PIPESTORE will enable improved yields of RES and will also encourage more people to consider RES. This will therefore result in increased RES market penetration and decreased fossil energy usage which will have a direct positive impact on CO2 emissions. In the solar scenario outlined in the previous section the additional annual emission reduction achieved would be 75kg per household (ie 300kWh times 0.25kg/CO2 per kWh of displaced gas). So if all 237,000 PIPESTORE systems sold to 2020 would be integrated with a solar thermal system of average size then this would decrease overall CO2 emissions by 17,775 tonnes in this year alone.

3.1.10 European Economic Benefits

PIPESTORE will result in significant financial benefits to Europe as a whole. First of all it will enable the consortium to introduce a radically novel means of storing thermal energy in the household. The total sales from PIPESTORE are estimated to be in the region of 190 EUROS million over 10 years. Production will be based in the EU by either the consortium members are licensees. PIPESTORE will therefore safeguard and create new jobs in the EU. Based on average sales of say 25 million EUROS per annum by year 7 of exploitation this would result in 350 full time jobs (assuming 50,000 EUROS as the value add per job).

List of Websites:
http://www.pipestore.eu/